Mutah University
College of Graduate Studies

An Improved Performance OFDM Channel Estimation Using Pilot-Symbol-Aided Technique

Done by
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Dedication

يا مُعَااااااااااذ ... يا رفيق الروح ... هذي الروح بَعدك تَتَنهد
تنبضُ حزناً والقلبُ يَبكي قهراً
والغضب يَتَمَدد
وإن رَحلَ الجمعُ حولَ رَفيقَتِكَ فهي
كسيـــــــــــــرةٌ تتوعد
يا مُعَاذ ما كنت مُخلِفاً موعِداً معي
واليومَ بجراحي أُكمِلُ حُلمَك... وانطر
الوعدَ يتجدد،،
ما العيش دونَك يا حبيباً ... والنبض
يا حبيبي نبضك يتفقد ....
يا مُعَاذ ما كُنتَ راحلاً دون وداع فعليكَ
الله يا رفيق دربي لِمَ عَزَّ في الحُضورِ
اللقاء ..... وما كُنتَ في ألمي مازحاً
يوما ..... وما تَرَكتَ رفيقتكَ ... لآلامِها ...
الأوصالُ منها تتلَحد ....
ياااااااااا مُعَاذ سَلِ الأقلامَ عني بَعدَك
وسَلْ بائسَ الأيامِ وسَلْ كاتبَ الهمومِ
كيف الرفيقةُ دونكَ تتمزق ... وكيفَ
الجسدُ من دمعِهِ يتَكَسر .... ويَتَصَفد
يا رفيق الروح يا غائباً ناجني بالأرواح
وانفخ بها الأمال في عروقي ودع العهد
ولا تدع الخيبة تنهش بقايايا وتتأبد
يا مُعَاذ ناظر الروح مني بسماء الرّقةِ
ترعد بويلات الألم ،، صرخاتها تعلو
يااااااا مُعَاااااااااذ يااااااا مُعَاذ ،، لكن
الحظ اغبر يتجسد ....
إليك يا مُعَاذ ... إليك يا
حبيبي ....
اليك يا بطلي ...
اليك يا زوجي ..
اليك ايها الطيار البطل الشهيد الملازم أول مُعَاذ الكساسبه
اليك ... أنت دون
سواك ...
أُهديكَ حُلمك .....

Anwar Yousef Al-Tarawneh

أنوار يوسف الطراونه

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Anwar Yousef Al-Tarawneh

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List of Abbreviations

1-D	One-Dimensional
2-D	Two-Dimensional
ADC	Analog-to-Digital Converter
AWGN	Additive White Gaussian Noise
BER	Bit Error Ratio
BW	BandWidth
CDMA	Code Division Multiple Access
CIR	Channel Impulse Response
CP	Cyclic Prefix
CSI	Channel State Information
DAB	Digital Audio Broadcasting
DAC	Digital-to-Analog Converter
CIR	Channel Impulse Response
dB	Decibel
DC	Direct Current
DDCE	Decision Directed Channel Estimation
DPSK	Differential Phase Shift Keying
dTTb	digital Terrestrial Television broadcasting
DVB	Digital Video Broadcasting
DFT	Discrete Fourier Transform
EUTRAN	Evolved Universal Terrestrial Radio Access Network
FDM	Frequency Division Multiplexing
FFT	Fast Fourier Transform
HD-DIVINE	High Definition DIgital VIdio Narrowband Emission
HPA	High Power Amplifier
IDFT	Inverse Discrete Fourier Transform
IEEE	Electrical and Electronic Engineers
IFFT	Inverse Fast Fourier Transform
ISI	Inter Symbol Interference
GSM	Global System for Mobile Communications
LMS	Least Mean-Square
LPF	Low Pass Filter
LSE	Least Square Estimator
MIMO	Multiple Input Multiple Output
ML	Maximum Likelihood
MMSE	Minimum Mean Square Error
MMSE-DC	Minimum Mean Square Error Diversity Combining
MR-DC	Maximal Ratio Diversity Combining
MSE	Mean-Square Error
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access

P/S	Parallel-to-Serial
PAPR	Peak to Average Power Ratio
PCMB	Parametric Channel Aided Modulation
PSA	Pilot-Symbol-Assisted
PSAM	Pilot Symbol Aided Modulation
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
S/P	Serial-to-Parallel
SNR	Signal-to-Noise Ratio
STERNE	System de Television En Radiodiffusion NumeriquE
SVD	Singular Value Decomposition
LOS	Line-Of-Sight

Abstract in English

An Improved Performance OFDM Channel Estimation Using Pilot Symbol Aided Technique

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Mutah University, 2015

Orthogonal Frequency Division Multiplexing (OFDM) provides an effective and low complexity means of eliminating inter-symbol interference over frequency selective fading channels. OFDM received a lot of interest in mobile communication research, as radio channel is usually a time variant and frequency selective.

The objective of this thesis is to improve channel estimation accuracy in OFDM system, because channel state information is needed for signal detection at the receiver, consequently, its accuracy affects the overall performance of the system. In practice, CSI can be reliably estimated at the receiver by transmitting pilot symbols along with data symbols. Pilot symbol assisted channel estimation is especially attractive for wireless channel, where the channel is time-varying. In this thesis, various efficient pilot assisted channel estimation schemes were investigated and compared for OFDM system.

Two major types of pilot arrangements, namely, block type and comb-type have been focused on this thesis. Block type pilot subcarriers, is particularly suitable for slow-fading radio channels, whereas, comb-type pilots arrangement exhibit better resistance to fast fading channels. The choice of channel estimation is of fundamental importance in OFDM receiver designs, which further involves a trade-off between complexity and estimation accuracy.

There are several methods for the estimation of the channel, namely; Least Square (LS), Minimum Mean Square Error and Modified Minimum Mean Square Error (LMMSE). The mathematical model for each of these estimators was derived and their performance was investigated on MATLAB. The results showed clearly that LS algorithm gives less complexity compared with MMSE and LMMSE but LMMSE algorithm provides comparatively better results.

A one dimensional (1-D) and two dimensional (2-D) pilot symbol assisted channel estimators for OFDM systems are simulated also for comparison purpose, The performance of the 2-D channel estimator is much better than that of the 1-D channel estimator of Mean Square Error (MSE) as a function of signal-to-noise ratio (SNR). Results showed that as the number of pilot symbols increases, the MSE decreases (i.e, improved performance).

الملخص

تحسين جودة تقييم القناة في نظام التقسيم الترددي المتعدد التعامدي باستخدام الرموز التجريبية

أنوار يوسف الطراونة

جامعة مؤته، 2015

تهدف هذه الرسالة إلى تحسين جودة تقييم القناة في نظام التقسيم الترددي المتعدد التعامدي لأن معرفة حالة القناة مطلوبة للكشف عن الإشارة في جهاز المستقبل، فجودة الإشارة تؤثر على الأداء العام لنظام التقسيم الترددي المتعدد التعامدي. عملياً، يتم تقييم حال القناة في جهاز المستقبل بإرسال رموز تجريبية مقرونة بالبيانات. في هذه الدراسة ، تمت دراسة ومقارنة عدة أنواع مختلفة من الرموز التجريبية المساعدة لتقييم القناة في نظام التقسيم الترددي المتعدد التعامدي.

وقد تم التركيز على نوعين رئيسيين من أنواع ترتيب الرموز التجريبية في هذه الرسالة، وهما النوع الفردي والنطاقي. إن اختيار نوع تقييم القناة غير ذي أهمية أساسية في تصميم جهاز المستقبل في نظام التقسيم الترددي المتعدد التعامدي، مما يتطلب الاختيار إما بين التعقيد أو تقييم الجودة. توجد عدة طرق لتقييم القناة تحديدا خوارزمية التخمين التربيعي الضئيل، خوارزمية أقل معدل خطأ تربيعي وأقل معدل خطأ تربيعي خطي. وقد تم استخراج الشكل الرياضي لكل من هذه المقيمات ودراسة أدائها باستخدام برمجية الماتلاب.

أظهرت الدراسة أن خوارزمية التخمين التربيعي الضئيل اقل تعقيداً مقارنةً مع خوارزمية أقل معدل خطأ تربيعي و خوارزمية أقل معدل خطأ تربيعي خطي، ولكن خوارزمية أقل معدل خطأ تربيعي خطي أظهرت نتيجة افضل من قرينتيها من الخوارزميات الأخرى. تمت برمجة مقيمات القنوات برموز تجريبية أحادية وثنائية البعد لنظام التقسيم الترددي المتعدد التعامدي ، حيث ظهر أن أداء مقيمات رموز البعد الثنائية كان أفضل من مقيمات رموز البعد الأحادي. أظهرت نتائج البرمجة أن معدل الخطأ التربيعي قد ظهر كمعامل لنسبة تشويش الإشارة، كما أظهرت انه بينما يزداد عدد الرموز التجريبية يقل معدل الخطأ التربيعي، وهذا يعني أن الأداء تحسن بشكل افضل.

Chapter 1
Introduction

1.1 Background

Over the past two decades, the rapid development of wireless communication technology has brought great convenience to people's life and work. In the 21st century, wireless communication technologies, particularly mobile communication technology, present unprecedented development. The goal of the next generation of mobile wireless communication system is to achieve ubiquitous, high-quality and high speed mobile multimedia transmission. To attain this goal, numerous technologies are constantly being applied to mobile communication systems. Academia and industry have reached a consensus that Orthogonal Frequency Division Multiplexing (OFDM) is one of the most promising core technologies in a new generation of wireless mobile communication system [Ballal, et al., (2013), Liu, et al., (2014)].

OFDM is a multi-carrier transmission technology in wireless environment, and can also be seen as a multi-carrier digital modulation or multi-carrier digital multiplexing technology. Because of using of orthogonal carrier technology without interference and no guard band between single carriers, OFDM system requires much less bandwidth compared with the conventional Frequency Division Multiplexing (FDM), and gets higher bandwidth utilization [Arora, et al., (2014), LaSorte, et al. (2008)].

OFDM is used to divide the frequency selective channel into a number of parallel, frequency sub channels. By making the sub-channels narrowband, the individual channels experience almost flat fading, and this makes receiver design simple. OFDM is a potential technique for transmitting high-bit-rate over indoor and outdoor wireless communication systems [Edfors, et al., (1996), Li (2000)].

The use of Differential Phase-Shift Keying (DPSK) in OFDM systems avoids the need for channel estimation and to track a time varying channel; however, it limits the number of bits per symbol and results in a 3 dB loss in Signal-to-Noise Ratio (SNR) compared with coherent modulation. Accurate channel estimation can be used in OFDM systems to improve their performance by allowing for coherent demodulation [Li, et al., (1998), Van de Beek, et al., (1995)].

A number of channel estimation techniques are reported in [Li, (2000), Morelli and Mengali, (2001), Hoeher, et al., (1997)]. In Pilot-Symbol-Assisted (PSA) techniques channel estimation is performed by inserting pilot symbols at selected positions in the OFDM time-frequency grid.

There are two main problems in designing channel estimators for wireless OFDM systems:

The first problem is the arrangement of pilot information, where pilot means the reference signal used by both transmitters and receivers.

The second problem is the design of an estimator with both low complexity and good channel tracking ability.

The two problems are interconnected [Edfors, et al., (1996)]. In general, the fading channel of OFDM systems can be viewed as a Two-Dimensional (2-D) signal (time and frequency) [Vidhya and Kumar (2013)]. The optimal channel estimator in terms of mean-square error is based on 2-D Wiener filter interpolation [Athaudage and Jayalath (2004)]. Unfortunately, such a 2-D estimator structure is too complex for practical implementation. The combination of high data rates and low bit error rates in OFDM systems necessitates the use of estimators that have both low complexity and high accuracy, where the two constraints work against each other and a good trade-off is needed. The One-Dimensional (1-D) channel estimations are usually adopted in OFDM systems to accomplish the trade-off between complexity and accuracy [Li (2000)].

The two basic 1-D channel estimations are block-type pilot channel estimation and comb-type pilot channel estimation, in which the pilots are inserted in the frequency direction and in the time direction, respectively [Coleri, et al., (2002)]. The estimations for the block-type pilot arrangement can be based on Least Square (LS), Minimum Mean Square Error (MMSE), and modified MMSE. The estimations for the comb-type pilot arrangement includes the LS estimator with 1-D interpolation, the Maximum Likelihood (ML) estimator, and the Parametric Channel Modeling-Based (PCMB) estimator [Coleri, et al., (2002)]. Other channel estimation strategies were also studied [Sanzi, et al., (2003)], such as the estimators based on simplified 2-D interpolations, the estimators based on iterative filtering and decoding, estimators for the OFDM systems with multiple transmit-and-receive antennas, and so on.

In OFDM systems, channel estimation is necessary to obtain the Channel State Information (CSI), reducing the bit error rate and also to achieve a distortion less output data [Tufvesson (2000)].

There are various methods to channel estimation such as: with or without a need for parametric models, blind or pilot based methods, frequency and/or time domain analysis and adaptive or non-adaptive techniques. Among these mentioned methods, channel estimation in OFDM systems is often done in the frequency domain using pilot symbols or training data [Li (2000)]. The LS and MMSE are conventional linear channel estimation techniques which are based on pilot arrangement. The LS method is less complicated and simple respect to other methods and consequently is used to channel estimation, but it has a serious drawback

which is more sensitive to channel noise [Van de Beek, et al., (1995)]. The MMSE estimator has better performance than LS method, but suffers from a high computational complexity because it requires knowledge of the channel statistics and SNR [Van de Beek, et al., (1995)]. Some different methods have been developed to reduce the complexity and improve the performance of the MMSE such as Singular Value Decomposition (SVD) [Edfors, et al., (1998)].

This thesis describes the pilot-based channel estimation in OFDM system and introduces the different types of the channel parameters estimators.

1.2 Literature Review

Channel estimation is a challenging problem in wireless systems because mobile radio channels are highly dynamic. To avoid channel estimation, one can adopt a differential modulation technique instead of coherent modulation. However, such a system typically results in lower data rates and can incur a 3-4 dB SNR [Proakis (2000)]. For OFDM systems which aim to provide high data rate and spectral efficiency, coherent modulation is more effective; hence, channel estimation is often required as an integral part of the receiver design.

The problem of channel estimation for cellular channels has been widely and successfully addressed in the literature. Estimation schemes capable of tracking the fading channel in cellular systems are an integral part of standardized such as Global System for Mobile Communication (GSM) and CDMA2000. A detailed description of various estimation schemes can be found in the excellent survey paper [Tong, et al., (2004)] and the references therein. However, channel estimation in relay-based systems is still an open problem. Whether the existing estimation schemes can cope up with the different underlying channel model in relay-based systems are not known yet.

Mobile-to-mobile channels undergo faster fading compared to cellular channels due to the increased mobility. Estimation schemes that can track this fast fading are required for mobile-to-mobile systems [Cavers (1991)].

Of different classes channel estimation techniques that have been developed in the literature, one class of techniques is based on pilot symbols which are known a priori to the receiver. In this case, a standard approach is a Pilot Symbol Aided Modulation (PSAM) [Cavers (1991)] or so called pilot assisted transmission [Athaudage and Jayalath (2004)], where known pilot signals multiplexed with information symbols are sent through the channel at regular intervals so the radio receiver can make direct measurements of the channel variations created by the propagation environment and terminal mobility.

Channel estimation for OFDM system in slow fading channels has been widely studied [Van de Beek, et al., (1995)], [Edfors, et al., (1998)]. However, those channel estimation techniques were developed under the assumption that the channel is constant over one OFDM symbol, an assumption that may not hold in some mobile applications.

Li et al [Li, et al., (1998)]. presented MMSE estimator by exploiting both time-domain and frequency domain correlations of the frequency response of rapid dispersive fading channels. In related work, Moon and Choi introduced a channel estimation algorithm by adopting a Gaussian interpolation filter or a cubic spline interpolation filter [Moon and Choi (2000)]. However, algorithms in both [Li, et al., (1998)] and [Moon and Choi (2000)] require knowledge of channel statistics, which may not be available. To make the estimation algorithm independent of the channel statistics, Li discussed in [Li (2000)] a robust implementation of the MMSE pilot-symbol-aided estimator which does not depend on channel statistics. In [Zhao and Huang (1997)], Zhao and Huang proposed a method employing low-pass filtering in a transform domain to estimate the channel transfer function for the pilot subcarrier. Then a high resolution interpolation is adopted to obtain the channel transfer function for non-pilot subcarriers.

In [Chang and Su (2002)], Chang and Su discussed a pilot-aided channel estimation method for OFDM systems operating on Rayleigh fading channels. The channel responses at the pilot subcarriers are estimated using an LS estimator and then interpolated to non-pilot subcarriers using a 2-D regression surface function. This estimator also does not require channel statistics.

Recently, Merli and Vitetta proposed a ML based algorithm for joint carrier frequency offset and Channel Impulse Response (CIR) estimation for OFDM system in [Merli and Vitetta (2008)]. The authors adopted a second-order Taylor series to simplify the estimation problem and derived an approximate closed form solution to the estimation problem. However, it was derived under the assumption that the channel does not change over one OFDM symbol. In [Merli and Vitetta (2008)], the frequency offset is assumed to be constant for all multipath implying that the Doppler frequency shift is neglected for individual multipath.

In this thesis, we study the channel estimation problem for OFDM systems in frequency selective fading channels. Three channel estimation algorithms are proposed [LS estimator, MMSE estimator and LMMSE estimator].

1.3 Thesis Outline

Channel estimation is a key technology of OFDM system, and its accuracy determines the quality of the system transmission. This thesis is on the research of pilot-based channel estimation of OFDM for wireless mobile system. The first two chapters introduce the wireless channel transmission characteristics and the impact on the OFDM system, and multipath fading channel model used in the thesis. The third chapter describes the development of OFDM technology, basic principles, structural features and key Limitation. The fourth chapter describes the pilot-based channel estimation in OFDM system. The thesis introduces the different types of the channel parameter estimators, investigate the impact of pilot allocation on channel estimation performance and explore the different methods used for channel estimation [LS estimator, MMSE estimator and modified MMSE estimator]. The fifth chapter presence the simulation results and compares the differences of the algorithms. The last chapter is about the conclusions and future work.

Chapter 2
Wireless Multipath Propagation Channel

2.1 Introduction

In wireless telecommunications, multipath is the propagation phenomenon that results in radio signals reaching the receiving antenna via two or more paths [Veeranna, et al., (2010)]. Causes of multipath include atmospheric ducting, ionospheric reflection and refraction, and reflection from water bodies and terrestrial objects such as mountains and buildings. The effect of multipath can cause errors and affect the quality of communications [McGraw (2010)].

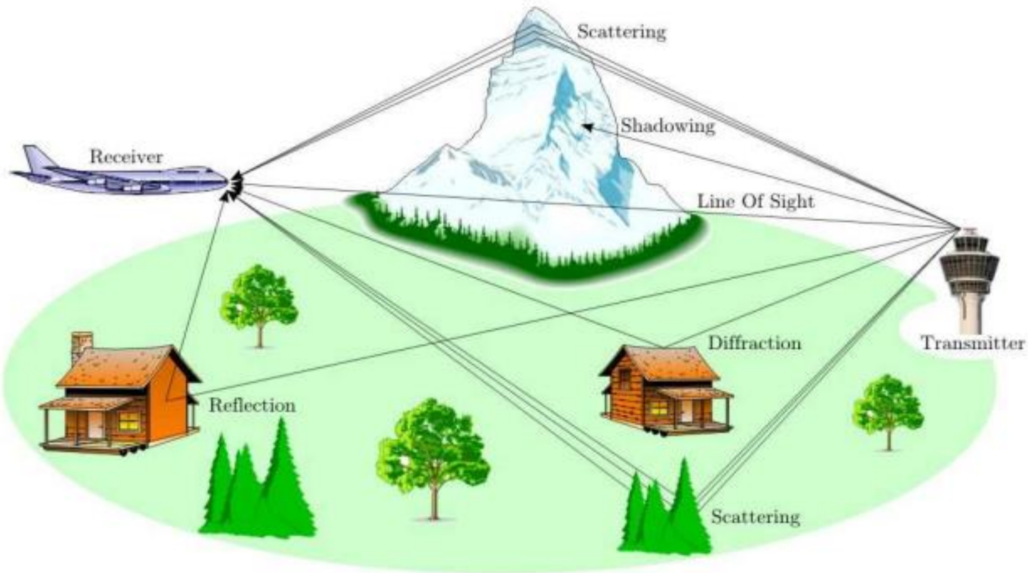

Figure 1 Propagation Component between the transmitter and the receiver

Fading happens when the antennas are residing below most surrounding structure of the area, that causing the absence of signal line of sight between the transmitting antenna and the receiving one, so even when line-of-sight exists the waves will arrive from different directions and different propagation delays which cause the signal to fade or distort [Chavan, et al., (2011)]. A typical propagation effect is shown in Figure 1.

Fading channel is one of the channel types which frequently occur in radio communication. There are numerous causes of fading including [Jamali, et al., (1994)].

1. One common cause of fading is the multipath nature. In this case, the transmitted signal arrives at the receiver from different paths with time-varying nature. These individual paths cannot be distinguished at the receiver's end and are all added together. Thus, the signal

becomes a replica of the transmitted one with random amplitude and phase.

2. The second kind of fading is caused by the electron density variation versus altitude in the ionospheric layers. The dynamic changes of ionospheric layers vary the length of the transmission path, and consequently, the received signal experiences random variations in both amplitude and phase.
3. Another significant cause of fading is the relative motion of the transmitter and receiver in a static multipath environment.

Fading may be large scale fading or small scale fading. Large-scale fading effects are dominant when the transmitter or receiver moves over distances greater than several tens of the signal wavelengths, and they play an important role in determining the cell coverage area, outages and handoffs. Small-scale fading is caused by multipath propagation. This effect plays an important role in determining link level performance in terms of bit error rates, averages fade duration and so on [Zajic (2012)].

2.2 Impulse Response Model of a Multipath Channel

The small-scale variations of a mobile radio signal can be directly related to the impulse response of the mobile radio channel. The impulse response is a wideband channel characterization and contains all information necessary to simulate or analyze any type of radio transmission through the channel [Rappaport (2001)]. This can be done by modelling the channel as a linear filter with a time varying impulse response. However, the impulse response of the channel is a useful characterization of the channel, since it may predict and compare the performance of many mobile communication systems and transmission bandwidths for a mobile channel condition [Arokiamary (2009)].

The baseband impulse response of a multipath channel can be expressed as [Proakis (2000)]:

$$h_b(t,\tau) = \sum_{i=0}^{N-1} a_i(t) e^{j(2\pi f_c \tau_i(t) + \varphi_i(t,\tau))} \delta(\tau - \tau_i(t)) \tag{2.1}$$

where a_i (t,τ) and τ_i (t) are the real amplitudes and excess delays, respectively, of the ith multipath component at time t. The phase term $2\pi f_c \tau_i$ (t) + φ_i (t,τ) in Equation (2.1) represents the phase shift due to the free space propagation of the ith multipath component, plus any additional phase shifts which are encountered in the channel.

2.3 Parameters of Mobile Multipath Channels

It is important to study the parameters of mobile multipath channels; some of the parameters are extracted from the power delay profile of the multipath channel. Some of the important parameters of mobile multipath channels are discussed below; namely:

(a) Time Dispersion

(b) Coherence bandwidth
(c) Doppler spread and coherence time

2.3.1 **Time Dispersion Parameters**

The time dispersion parameters are helpful in quantifying the different multipath channel profiles so that it is possible to compare several multipath channels [Arokiamary (2009)].

The following are delayed profiles are multipath channel parameters that have to be measured accurately.

i) Mean Excess Delay

The mean excess delay is the first moment of the power delay profile and is defined to be:

$$\bar{\tau} = \frac{\sum_k a_k^2 \tau_k}{\sum_k a_k^2} = \frac{\sum_k P(\tau_k)\tau_k}{\sum_k P(\tau_k)} \tag{2.2}$$

where $P(\tau)$ is the power measured at time τ

ii) R.M.S. Delay Spread

The Root-Mean-Square (RMS) delay spread is the square root of the second central moment of the power delay profile and is defined to be:

$$\sigma_\tau = \sqrt{\bar{\tau}^2 - (\bar{\tau}\,)^2} \tag{2.3}$$

where $\bar{\tau}$ is average (mean) excess delay value,

$$\overline{\tau^2} = \frac{\sum_k a_k^2 \tau_k^2}{\sum_k a_k^2} = \frac{\sum_k P(\tau_k)\tau_k^2}{\sum_k P(\tau_k)} \tag{2.4}$$

iii) Excess Delay Spread

2.3.2 **Coherent Bandwidth**

The coherence bandwidth B_c is a statistical measure of the range of frequencies over which the channel can be considered to be "flat" [Misra (2013)]. Coherent bandwidth is the range of frequencies over which two frequency components have a strong potential for amplitude correlation [Han, et al., (2013)].

If the frequency correlation between two multipath is above 90%, then the coherence bandwidth is approximately

$$B_c \approx \frac{1}{50\sigma_\tau} \tag{2.5}$$

If the frequency correlation is above 50%, then the coherent bandwidth is [Agrawal and Zeng (2011)]:

$$B_c \approx \frac{1}{5\sigma_\tau} \tag{2.6}$$

2.3.3 **Doppler Spread and Coherent Time**

Doppler spread and coherent time describe the time-dispersive nature of the channel in a local area, but they do not offer information about the time-varying nature of the channel caused by the relative motion of the transmitter and the receiver [Han, et al., (2013)].

When a pure sinusoidal tone of f_c is transmitted, the received signal spectrum, called the Doppler spectrum, will have components in the range $f_c - f_d$ and $f_c + f_d$, where f_d is the Doppler shift. This is shown in Figure 2. The parameter coherence time and Doppler spread are inversely proportional to each other. It is given as:

$$T_c = \frac{1}{f_m} \tag{2.7}$$

where $f_m \rightarrow$ maximum Doppler shift given by $f_m = {}^{v}/_{\lambda}$, $v \rightarrow$ Speed of the mobile, $T_c \rightarrow$ Coherence time and $\lambda \rightarrow$ Wavelength.

Coherence time is a statistic measure of time duration where the impulse response of the channel is invariant [Arokiamary (2009)].

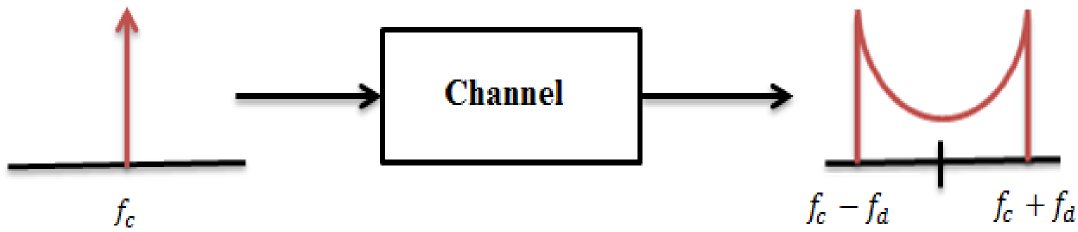

Figure 2 Demonstration of Doppler spread and coherent time effect

2.4 Types of Small-Scale Fading

The type of fading experienced by the signal through a mobile channel depends on the relation between the signal parameters (bandwidth, symbol period) and the channel parameters (rms delay spread and Doppler spread). Hence we have four different types of fading. Figure 3 shows a tree of the four different types of fading.

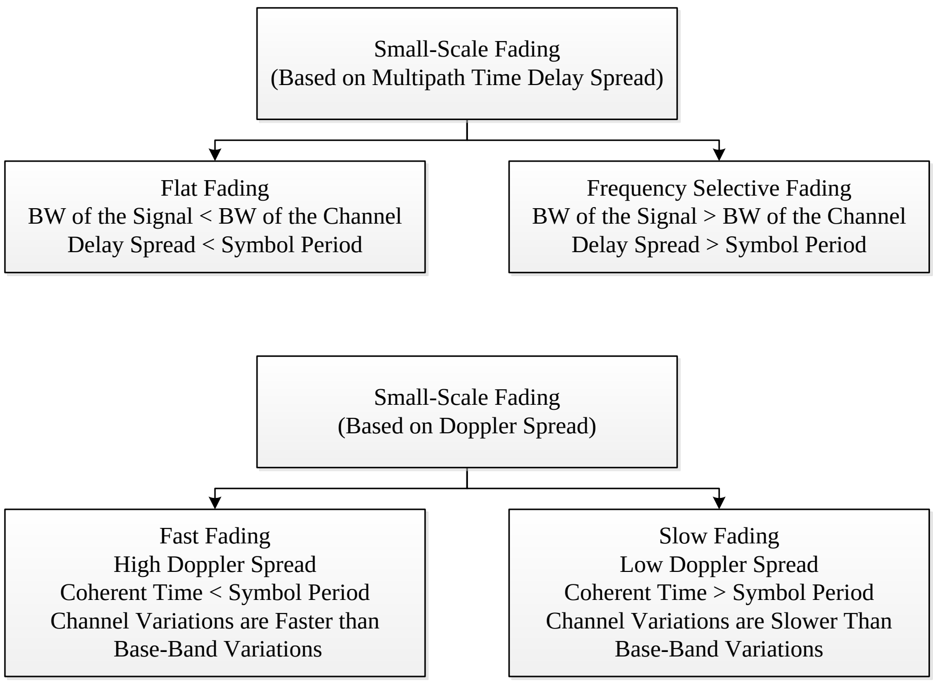

Figure 3 Types of Small-Scale Fading

2.4.1 **Fading Effects Due to Multipath Time Delay Spread**

Time dispersion due to multipath causes the transmitted signal to undergo either flat or frequency selective fading.

2.4.1.1 Flat Fading

If a mobile radio channel has a constant gain and linear phase over a bandwidth which is greater than the bandwidth of the transmitted signal, the received signal will undergo flat fading [Singh (2008)]. Equivalently if the symbol period of the signal is more than the rms delay spread of the channel, then the channel is flat fading.

So we can say that the flat fading occurs when:

$$B_S \ll B_C \tag{2.8}$$

where B_S is the signal bandwidth and B_C is the coherence bandwidth. Also

$$\sigma_\tau \ll T_S \tag{2.9}$$

where T_S is the symbol period and σ_τ is the rms delay spread.

Flat fading channels are also called narrowband channels, since the bandwidth of the applied signal is narrow as compared to the channel flat fading bandwidth [Li (2000)].

2.4.1.2 Frequency Selective Fading

If the channel possesses a constant-gain and linear-phase response over a BW that is smaller than the BW of the transmitted signal, then the channel creates frequency selective fading [Engles and Petre (2006)]. Frequency selective fading channel is also called wideband channels, since the bandwidth of the signal is wider than the bandwidth of the channel impulse response.

To summarize, a signal undergoes frequency selective fading if

$$B_s > B_c \tag{2.10}$$

$$\sigma_\tau > T_S \tag{2.11}$$

2.4.2 **Fading Effects Due to Doppler Spread**

Depending on how rapidly the transmitted baseband signal changes as compared to the rate of change of the channel, a channel may be classified either as a fast fading or slow fading channel [Rappaport (2001)].

2.4.2.1 Fast Fading

In a fast fading channel, the characteristics change rapidly compared with the symbol duration of the transmitted signal, i.e. the symbol (T_s) of the transmitted signal is much greater than the coherence time of the channel (T_c). The coherence time of the channel is a statistical measure of the time duration over which the channel characteristic is invariant. Due to Doppler spread, this type of fading which also called (time-selective

fading) will cause signal distortion which increase with increasing Doppler spread [Engles and Petre (2006)].

Slow fading occur when the channel characteristic changes slower than the symbol duration of the transmitted signal ($T_S \ll T_C$). Therefore the channel can be assumed to be static over one or several symbol durations [Das (2013)].

It should be clear that the velocity of the mobile (or velocity of objects in the channel) and the base-band signaling determines whether a signal undergoes fast fading or slow fading [Rappaport (2001)].

2.5 OFDM Channel Model

2.5.1 AWGN Channel

AWGN is a noise that affects the transmitted signal when it passes through the channel. It contains a uniform continuous frequency spectrum over a particular frequency band. AWGN channel is the simplest channel and the only parameter in the SNR (dB) [Vidhya and Shankar (2013)]. Figure 4 shows the AWGN channel model.

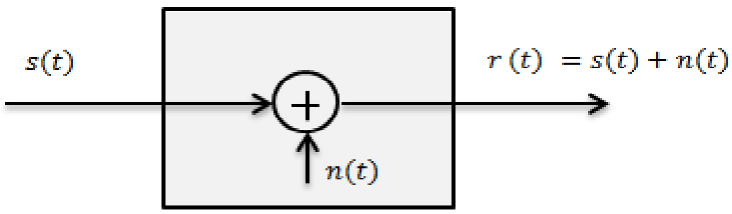

Figure 4 AWGN channel

where $y(t)$ is the received signal $s(t)$ is the modulated signal transmitted through the channel which is corrupted by AWGN and $n(t)$ is AWGN with zero mean and variance $\sigma^2 = \frac{N_o}{2}$ (N_0 is the noise power spectral density).

2.5.2 Rayleigh Multipath Channel

The Rayleigh fading model assumes that the magnitude of the signal that has passed through transmission medium will vary randomly, or fade, according to a Rayleigh distribution [Vidhya and Shankar (2013)].

In a wireless transmission system where the receiver is in motion relative to the transmitter with no line-of-sight path between their antennas and when there are many objects in the environment that scatter the radio signal before it arrive at the receiver, the Rayleigh fading is most applicable [Chavan, et al., (2011)].

The term Rayleigh fading refers to a multiplicative distortion $h(t)$ of the transmitted signal $s(t)$, as in

$$y(t) = h(t).s(t) + n(t) \qquad (2.12)$$

where $y(t)$ is the received waveform and $n(t)$ is the AWGN. Figure 5 shows the Rayleigh multipath channel.

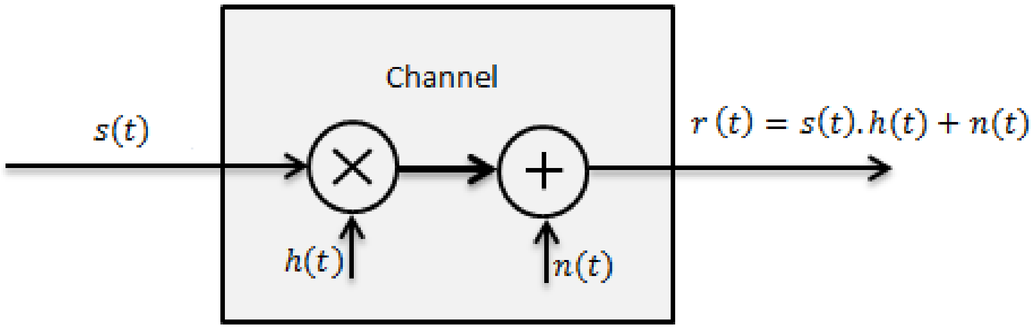

Figure 5 Rayleigh multipath channel

2.6 Chapter Summary

The wireless channel impasses fundamental limitation on the performance of wireless communication systems. The transmission path between the transmitter and the receiver can be altered from a simple Line Of Sight (LOS) to one that is drastically obstructed by buildings, foliage and mountains, etc….,

Impairment in the propagation channel has the effect of disturbing the information carried by the transmitted signal. Channel disturbance can be a combination of additive noise, multiplicative fading and distortion due to time dispersion.

There are a lot of mechanisms behind the electromagnetic wave propagation, but they can be generally attributed to reflection, diffraction and scattering. Reflections arise when the Propagating wave impinges on an object that is larger as compared to its wavelength. Diffraction occurs when the Radio path between a transmitter and a receiver is obstructed by a surface with sharp irregular edges. Scattering When objects are smaller than the wavelength of the propagating wave, the incoming signal is scattered into several weaker outgoing signals.

Fading is classified based on the relationship between the signal parameters and the channel parameters. The coherence time of a channel is a measure of how quickly the channel response de-correlates. When the symbol duration is small compared to the coherence time the fading is termed as slow fading. When the symbol duration is comparable to the coherence time of the channel the fading is termed fast. Another classification of the fading process depends on the relationship between the delay spread of the channel which is a measure of its time depressiveness

and the symbol duration. When the delay spread is much smaller than the symbol duration the fading is classified as flat and when it is not it is termed as frequency selective fading.

Briefly; in this chapter fading phenomenon is introduced. The main characteristics of fading channel are also shown. The next chapter provides an initial overview of orthogonal frequency division multiplexing (OFDM).

Chapter 3
Orthogonal Frequency Division Multiplexing

3.1 Introduction

Multicarrier networks such as Frequency Division Multiplexing (FDM) have been around since the late 1950's [Doelz, et al., (1957)]. However, due to inefficient use of the frequency band and their implementational complexity they were restricted to military applications. A multicarrier system is a number of information bearing carriers transmitted in parallel. In wireless applications, the multicarrier systems are less prone to channel induced distortion than single carrier systems at corresponding data rates [LaSorte, et al., (2008)].

Chang [Chang (1966)] and Saltzberg [Saltzberg(1967)] further developed FDM in the mid 60's by introducing multiple carriers, which overlap in the frequency domain without interfering with each other, thereby improving the efficiency of frequency spectrum, hence OFDM.

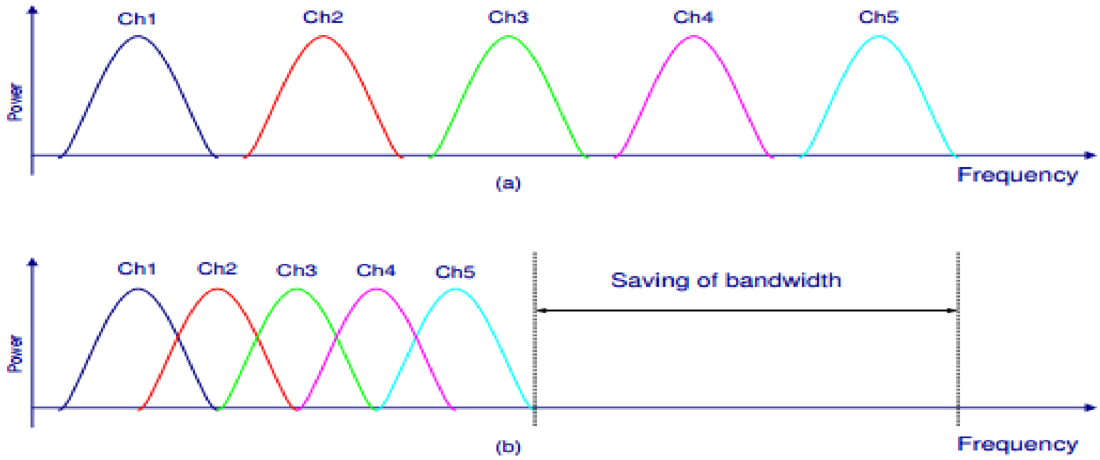

Figure 6 Comparison between conventional FDM and OFDM

OFDM divide the single high-data-rate stream into a number of lower rate streams which are transmitted simultaneously over some narrower sub-channels. So it is not only a modulation (frequency modulation) technique, but also a multiplexing (FDM) technique [Veeranna, et al., (2010)]. The difference between conventional FDM and OFDM is shown in Figure 6.

In the last 10 years, advances in particularly in Europe, where various projects and prototypes were initiated such as DIgital VIdeo Narrowband Emission (HD-DIVINE), System de Television En Radiodiffusion NumeriquE (STERNE), and digital Terrestrial Television broadcasting (dTTb). This has led to the adoption of OFDM in many European standards [Tirodkar and Patil (2015)].

OFDM has progressed to the point where it has now been used for various communication applications such as Digital Audio Broadcasting

(DAB) and Digital Video Broadcasting (DVB) in Europe [Tirodkar and Patil (2015)]. It has also been adopted as the physical layer modulation scheme for wireless networking standards such as Hiperlan2 in Europe and the Institute of Electrical and Electronic Engineers (IEEE) 802.11a, g standards in the United States [Arora, et al., (2014)].

However, while OFDM successfully alleviate the problem of dispersive channels, there are still some problems which need to be addressed such as time and frequency synchronization, frequency selective fading and the Peak to Average Power Ratio (PAPR) [Tirodkar and Patil (2015)].

3.2 OFDM Implementation of Multicarrier Modulation

3.2.1 **Orthogonality in OFDM**

In OFDM, the sub-carriers have overlapping spectra. In order for the receiver to separate them without ICI, these sub-carriers need to be orthogonal, hence the name orthogonal frequency division multiplexing (OFDM). Orthogonality can be shown by using orthogonal waveforms as follow [Arora, et al., (2014)]:-

$$\int_0^{T_s} \varphi_k(t)\varphi_l^*(t)\,dt = \begin{cases} 0, k \neq l \\ C, k = l \end{cases} \tag{3.1}$$

where C is a constant

Normally, FDM systems do not have this property. Each carrier is separated with a guard band to avoid Inter Carrier Interference (ICI) at the cost of low spectral efficiency, which is, besides presenting implementation difficulties, another drawback of FDM. OFDM, due to the orthogonality of overlapped sub-carriers, is a bandwidth efficient communication scheme [Ahamed (2008)]. Although the sub-channels overlap in frequency, they can be separated from one another by orthogonality. Figure 7 illustrates the orthogonality of carriers.

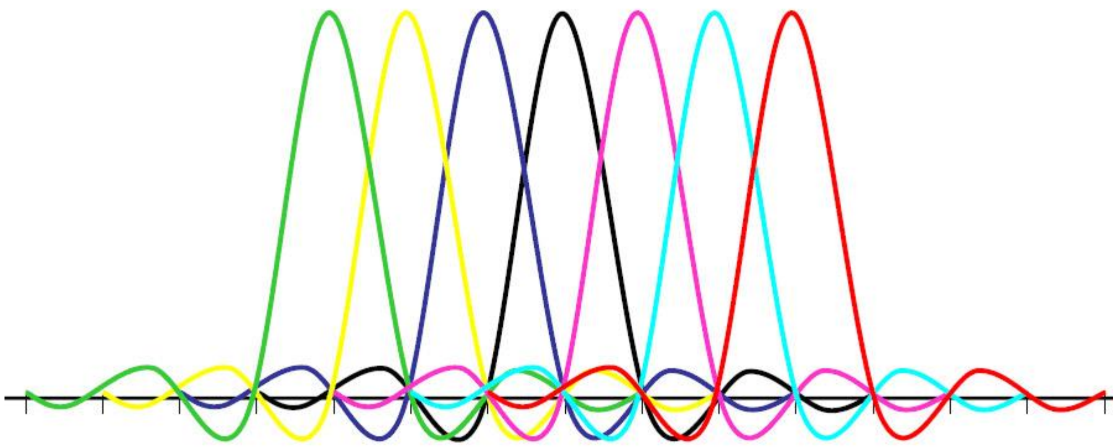

Figure 7 Orthogonality of sub-carriers

3.2.2 Use of Fourier Transform for Modulation and Demodulation

Inverse Discrete Fourier Transform (IDFT) and Discrete Fourier Transform (DFT) are used to perform the baseband modulation and demodulation respectively in order to make multicarrier systems a more practical technology. Also, they are used to exploit the sinusoidal nature of the Fourier transform basic functions [Arioua and Hassani (2014)]. Figure 8 shows a block diagram of a basic OFDM system in the base band utilizing the IDFT, DFT pair.

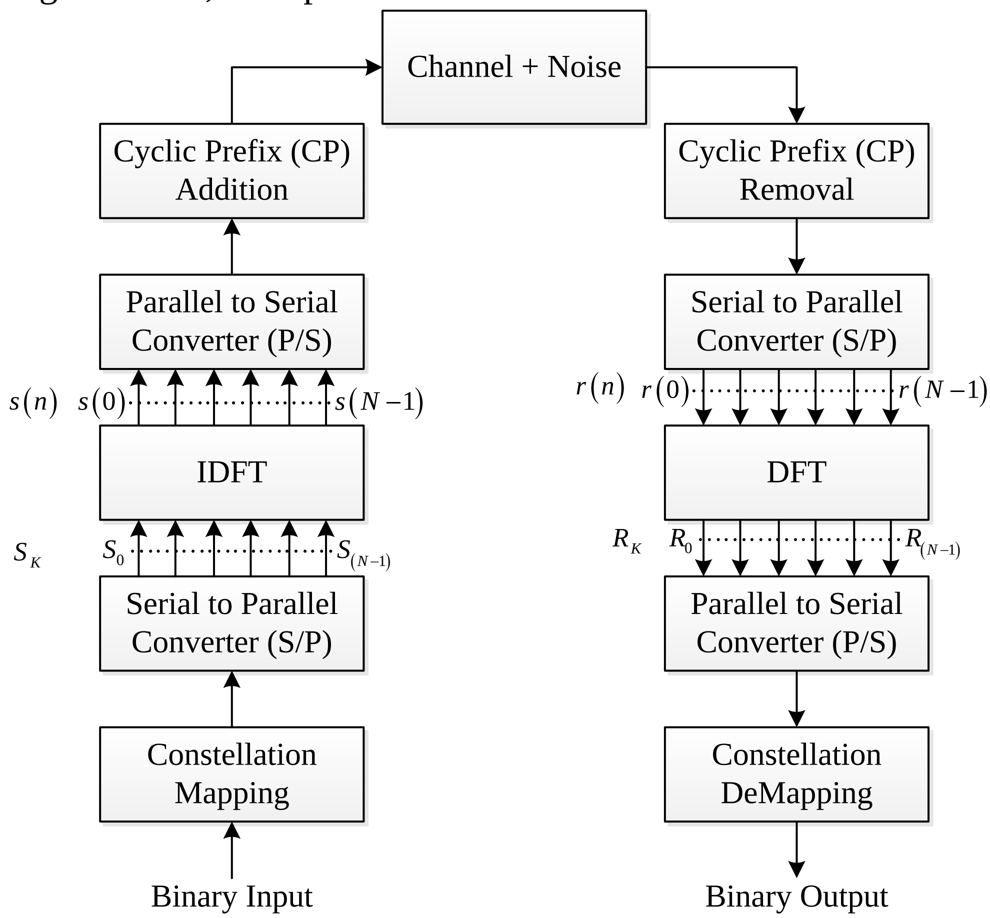

Figure 8 Basic OFDM System in the Baseband

Equation (3.2) illustrates exactly the IDFT operation [Arora, et al., (2014)]

$$s(n) = IDFT\left\{\sum_{n=0}^{N-1} s(n)e^{-\frac{j2\pi kn}{N}}\right\} \qquad k = 0,1,\ldots\ldots,N-1$$
$$= \frac{1}{N}\sum_{k=0}^{N-1} S_k e^{j2\pi kn/N} \qquad n = 0,1,\ldots.,N-1 \qquad (3.2)$$

where n are the discrete sampling points. This equation illustrates exactly the IDFT operation. The more efficient form of IDFT and DFT, The Inverse Fast Fourier Transform (IFFT) and Fast Fourier Transform (FFT), is used for modulation and demodulation [Arora, et al., (2014)].

In figure 8 the serial data stream is first mapped to a complex data symbol (Phase Shift Keying (PSK), Quadrature Amplitude Modulation

(QAM), etc.) with a symbol rate of $1/T_s$. Then the data enter a serial to parallel converter which is demultiplexed in a block of N complex symbols $S_k = S_0, S_1, \dots \dots, S_{N-1}$. The parallel samples, then pass through an N point IDFT, resulting in complex sample $s(n) = s_0, s_1, \dots \dots, s_{N-1}$.

Now if we assume that the incoming data is random, then IDFT is a set of N independent random complex sinusoids summed together. $s(n)$ is then converted back into a serial data stream producing a baseband OFDM transmit symbol of length $T = N.T_s$ [Manish and Agrawal (2013)].

At the transmitter we use a Cyclic Prefix (CP), that is a copy of the last part of the sample, and this CP is added to the head of the serial data stream before radio frequency (RF) up conversion and transmission [Parihar andSharma (2014)].

In the receiver this process is reversed to recover the transmitted data, the CP is removed prior to the DFT that reverses the effect of the IDFT. Then the complex symbols at the output of the DFT, $R_k = R_0 \dots \dots . R_{N-1}$ are decoded and the original bit steam recovered.

The demodulation process (assuming no CP and no channel impairments) using the DFT is:

$$\begin{aligned} R_k &= DFT\{r(n)\} \\ &= DFT\left\{\frac{1}{N}\sum_{k=0}^{N-1} R_k\ e^{j2\pi kn/N}\right\} \\ &= \sum_{n=0}^{N-1} r(n)\ e^{-j2\pi nk/N} \end{aligned} \tag{3.3}$$

3.3 OFDM Transmission over Time Varying Channels

OFDM is being primarily deployed in the wireless environment. This section describes properties of the wireless channel and describes the advantages and disadvantages of OFDM in this environment.

3.3.1 Multipath Propagation

The wireless channel is a harsh one, electromagnetic signals travelling through this medium is filled with disruptive and warping effects. The transmitted signal reaches the receiver through many paths, where the signal is reflected, diffracted and scattered by mountains, buildings, trees and other obstacles so that the multiple copies of the same transmitted signal arrive at the receiver affecting other symbols. And due to the occurrence of Inter Symbol Interference (ISI), which degrades the Bit Error Rate (BER) [Chavan, et al., (2011)].

3.3.2 Use of a Cyclic Prefix

To protect the OFDM symbols from multipath a CP with a length of N_g is used. The CP is a copy of the last part of the sample of an OFDM transmit block added to the front before transmission. So the transmitted

signal is therefore $N+N_g$. CP length should be about two times the RMS delay spread. [Zhao-yang and Li-feng (2003)].

The CP both preserves the orthogonality of the subcarriers and prevent ISI between successive OFDM symbols [Van de Beek, et al., (1995)]. Therefore, equalization at the receiver is very simple. This often motivates the use of OFDM in wireless systems. Figure 9 shows OFDM without CP and with CP.

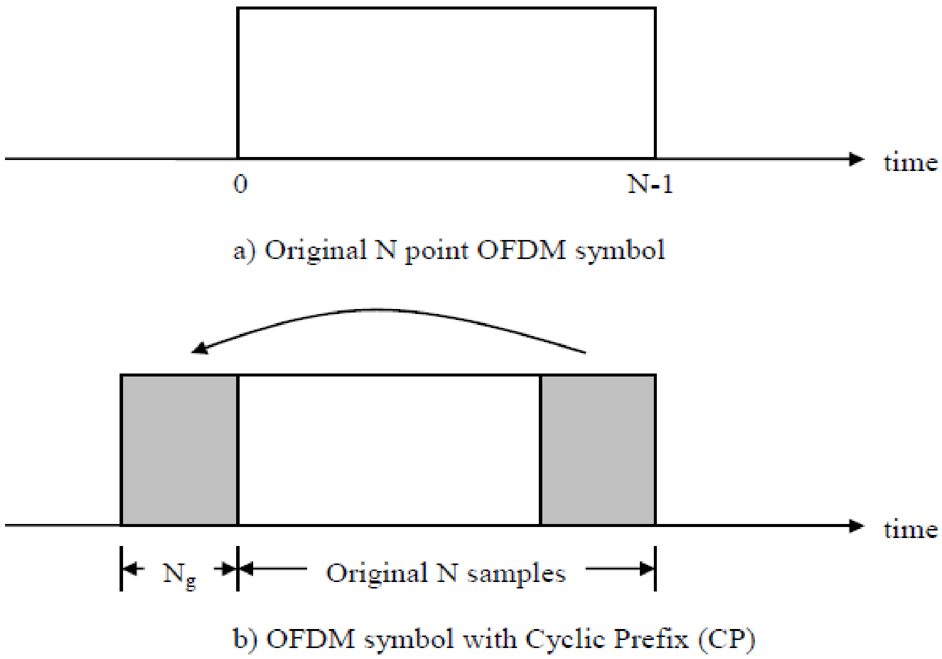

Figure 9 OFDM symbol a) without CP, and b) with CP

3.3.3 **Frequency Selective Fading**

CP is used to combat successfully the multipath propagation. The reciprocal effect of multipath propagation in the time domain is the frequency selective fading. When the channel has a constant magnitude and phase response over a bandwidth which is smaller than the bandwidth of the transmitted signal, the channel generates frequency selective fading [Rappaport (2001)]. According to this condition the signal experience multipath introducing ISI.

3.3.4 **Equalization**

In order to correct the effect of fading by the receiver, equalization is performed at the receiver, which is based on the channel properties and modulation schemes. Equalization is the process that is used to measure the channel response and use this information to correct the received signal. Several methods have been suggested, one of these methods utilizes pilot tones [Morelli and Mengali (2001)], [Hoeher, et al., (1997)], [Coleri, et al.,

(2002)] which are certain subcarriers with a known phase and amplitude at the receiver. Other methods use blind estimation techniques [Shentu and Armstrong (2001)], [Tufvesson (2000)] which do not require pilot tones.

3.4 Advantages of OFDM

Advantages of OFDM are listed as follows:

1. OFDM makes resourceful utilization of the spectrum by overlapping. By dividing the channel into a narrowband flat fading sub channel, OFDM is more resistance to frequency selective fading than single carrier systems.
2. High capacity and co-exist with current and future systems.
3. It reduces ISI and ICI through the use of a cyclic prefix and fading caused by multipath propagation.
4. High-speed wireless broadband multimedia networks.
5. OFDM is computationally capable of using FFT techniques to implement the modulation and demodulation functions.
6. It is robust against narrow-band co-channel interference.

3.5 Limitation in OFDM

Previous sections have detailed the advantages of OFDM; however the advantages are offset by some problems that are unique to OFDM.

3.5.1 **Synchronization**

Frequency and time synchronization are a major drawback in OFDM, the following section detail the problem and provide a basic introduction and solutions for these problems.

3.5.1.1 Timing Errors

The process of finding the start of a symbol in the receiver known as timing synchronization [Schmidl and Cox (1997)]. When the timing mismatch is within the cyclic prefix, the demodulation generates a linear phase rotation at the output of the FFT that can be corrected with a channel estimator.

When the timing mismatch is not corrected, inter symbol interference is produced. And because of that a sufficient length of the CP needs to be chosen. Another technique is to use pilot based methods [Webb and Keller (2000)] which uses certain carriers with a known phase and amplitude at the receiver.

3.5.1.2 Frequency Errors

Frequency offset errors are caused by mismatch between Doppler shift, RF oscillators and phase noise caused by nonlinear channel. Multicarrier

systems (such as OFDM) are more sensitive to frequency offset than single carrier systems.

Recommended solutions to frequency synchronization (such as symbol synchronization) are based on CP and pilot symbols are used in [Edfors, et al., (1996)] where the time and frequency synchronization are closely related. By decreasing the number of subcarriers within a set bandwidth, frequency sensitivity can be made more robust. Reducing the number of subcarriers within a set bandwidth will increase the frequency distance between subcarriers [Lakhendrakumargupta, et al., (2013)].

3.5.1.3 Carrier Phase Noise

The mismatch in the RF oscillators in the receiver and transmitter produces carrier phase noise which manifests itself in the baseband as amplitude attenuation and additional phase rotation [Edfors, et al., (1996)]. The effect of phase noise is more pronounced in differential detection schemes than coherent detection schemes [Edfors, et al., (1996)].

3.5.2 **Peak-to-Average Power Ratio**

High instantaneous signal peak with respect to the signal average power is another limiting aspect of multicarrier and OFDM modulation [Schugers and Srivastava (2001)]. Large peaks are due to superposition of N random phase sine wave in the IFFT.

Peak-to-Average Power Ratio (PAPR) is the relation between the maximum power of a sample in a given OFDM transmit symbol divided by the average power of that OFDM symbol [Manish and Agrawal (2013)].

$$PAPR = \frac{P_{peak}}{P_{average}} = \frac{max[|x_n|^2]}{E[|x_n|^2]} \tag{3.5}$$

The drawback of the high PAPR is that the dynamic range of the power amplifier (PA) and digital-to-analog (D/A) converters required during the transmission and reception of the signal is higher.

Many papers have been published to overcome the peak to average power ratio (PAPR) of the highly fluctuating transmit signal envelope. Two methods can be used to overcome such problem: distorted techniques which deliberately reduce peaks, but increase distortion and therefore BER, and distortionless techniques that attempt to generate a transmit signal with a low PAPR without affecting BER of the data.

3.6 Chapter Summary

This chapter introduced fundamental properties of OFDM, identifying its advantages and discussing its limitation. Specifically the history of multicarrier networks was discussed and its evolution towards OFDM. The introduction of the Fourier transforms and the efficient use of the frequency spectru Manish and Agrawal (2013)]. m with orthogonally spaced

subcarriers were shown to make OFDM a practical technology for the next generation of digital communications.

OFDM transmission over wireless channels was discussed focusing on multipath propagation and the advantages of OFDM in this medium. The use of the cyclic prefix in OFDM was shown to reduce the equalizer complexity dramatically down to one tap per subcarrier. Frequency selective fading was also introduced as a major advantage of OFDM where due to the long effective symbol time OFDM subcarriers experience flat fading.

Limitations of OFDM were analyzed next, with the two main disadvantages; synchronization errors and PAPR. Synchronization errors were shown to include timing errors, carrier phase noise, and frequency errors. PAPR due to the Rayleigh distributed samples at the output of IFFT were also briefly introduced and shown to have a degrading effect on the quality of OFDM systems.

Chapter 4
Pilot-Symbol-Aided Channel Estimator, Simulation Results, Conclusion and Future Work

4.1 Introduction

The estimation of the mobile radio channel is important where by it determines the channel status and limits the effect of the fading in the signal. The estimation of the mobile radio channel can be obtained in many methods. In this thesis, we investigate one of these methods, namely; Pilot-Symbol-Aided.

It is important to estimate the channel characteristics, especially in mobile wireless network systems where the channel changes over time, caused by transmitter and/or receiver being in motion at vehicular speed. The acknowledge of the impulse response of mobile wireless propagation channels in the estimator helps in getting important information for testing, planning and designing the wireless communication systems [Batav and Chourassiya (20130].

There are two different types of the channel parameter estimators: the decision-directed and pilot-symbol-aided. Decision Directed Channel Estimation (DDCE) uses the channel estimation of a previous OFDM symbol for the data detection of the current estimation, and then using the newly detected data for the estimation of the current channel [Kurpiers (2000)].

The decision directed channel estimation suffers from two basic problems: The assumption of correct data detection and the use of outdated channel estimates [Krishnaveni, et al., (2013)]. When the channel is varying very slowly; the use of outdated channel estimates does not create a serious problem. However, the outdated channel estimates for the previous OFDM symbol are no longer valid for the use of the data detection in the current OFDM symbol when the channel starts varying faster. For this reason, the error in data detection and channel estimation builds up to make the system performance unacceptable [Hanzo, et al., (2003)].

The second type of channel estimation is the pilot symbol aided channel estimation, which is used to estimate the CIR by having some symbols included in the message frame known to the transmitter (T_x) and receiver (R_x) to make it possible to realize any change or any error happens to these symbols using OFDM technique and in this way we have some knowledge to the channel state at the time of sending data.

For pilot based channel estimation of OFDM system, the following three criteria are required. Firstly, a suitable pilot pattern needs to be considered. Secondly, pilot-based channel estimation algorithm with low complexity

should be identified. Thirdly, proper demodulation method toward effective channel estimation has to be developed [Tong, et al., (2004)].

4.2 Pilot Based Channel Estimation

Coherent OFDM detection needs channel estimation and tracking, and for this reason, known pilots (symbols) are often multiplexed into the data, and therefore, the channel estimation can be accomplished by interpolation.

Pilot based channel estimation is the most common technique for channel estimation. Where it is based on Pilot Symbol-Assisted Modulation (PSAM), it depends on the transmission of pilot symbols which are known at the receiver [Hoeher and Robertson (1997)]. The pilot symbols are inserted into the data stream and then transmitted periodically over the mobile radio channel in time and frequency domain, and are spread over the entire bandwidth (BW) provided for data transmission.

In the receiver side these pilot symbols are analyzed to achieve channel estimation and finally the data symbols are estimated at the receiver [Van de Beek, et al., (1995)]. Figure 10 below describes an OFDM system that utilizes Pilot-based channel estimation method for equalization at the receiver end.

In this figure the binary input data at the transmitter is first grouped and mapped according to a specific modulation (Quadrature Phase Shift Keying (QPSK), 16QAM, and 64QAM) in "signal mapper", then the modulated data undergoes Serial-to-Parallel (S/P) conversion. After inserting known pilot symbols - either to all sub-carriers with a specific period or uniformly between the information data sequence- a frequency domain transmitted data S_k will be formed. IDFT block is used to transform the data sequence of length $N\{S_k\}$ into time domain signal $s(n)$ with the following equation [Arora, et al., (2014)]:

$$\begin{aligned} s(n) &= IDFT\,\{\textstyle\sum_{n=0}^{N-1} s(n)e^{-\frac{j2\pi kn}{N}}\,\} \qquad ,k = 0,1,\ldots\ldots,N-1 \\ &= \tfrac{1}{N}\textstyle\sum_{k=0}^{N-1} S_k e^{j2\pi kn/N} \qquad ,n = 0,1,\ldots.,N-1 \end{aligned} \tag{4.1}$$

Where N is the DFT length. Following the IDFT block, cyclic prefix to prevent Inter-symbol interference (ISI) is then pre-appended to $s(n)$ forming $s_g(n)$ vector.

After parallel to serial conversion (P/S), digital to analog conversion (D/A) and low pass filtering (LPF), the transmitted signal $s_g(n)$ will pass through the frequency selective time varying fading channel $h\,(n)$ with additive white Gaussian noise (AWGN) $z(n)$. And therefore the received signal is given by:

$$r_g(n) = s_g(n) * h(n) + z(n) \tag{4.2}$$

where $z(n)$ and $h(n)$ are AWGN and the channel impulse response respectively.

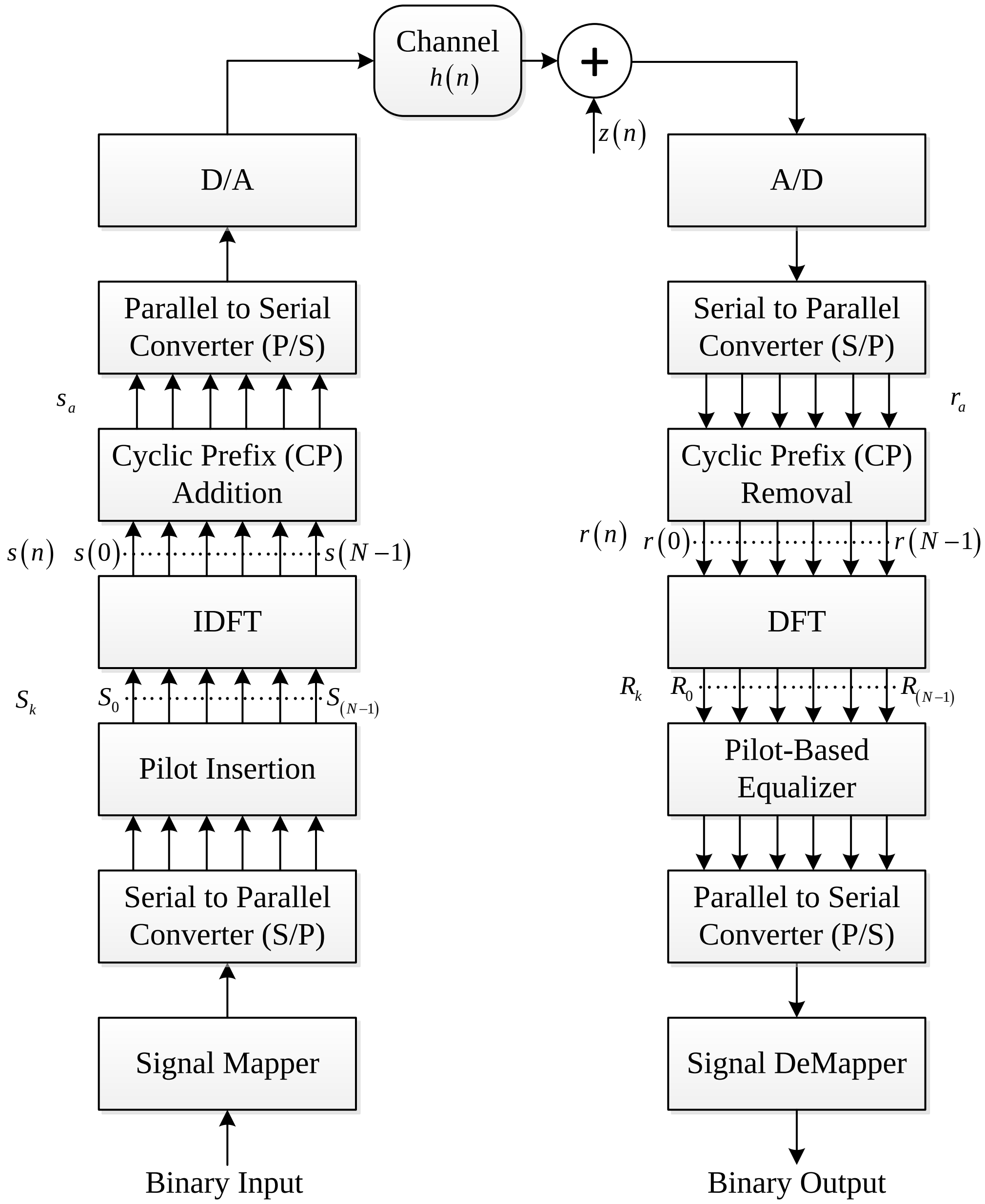

Figure 10 Pilot Based OFDM Model

At the receiver, after passing to discrete domain through Analog to Digital conversion (A/D) and LPF, the received signal goes through an S/P conversion and is stored in $r_g(n)$. The CP is then removed from $r_g(n)$ generating $r(n)$ which is then sent to DFT block for the following operation:

$$
\begin{aligned}
R_k &= DFT\{r(n)\} \\
&= DFT\left\{\frac{1}{N}\sum_{k=0}^{N-1} R_k\ e^{j2\pi kn/N}\right\} \qquad n = 0,1,\ldots,N-1 \\
&= \sum_{n=0}^{N-1} r(n)\ e^{-j2\pi nk/N} \qquad k = 0,1,\ldots,N-1 \qquad (4.3)
\end{aligned}
$$

After that equalization is applied using a pilot-based channel estimation method, and the pilot symbols are removed from equalized signal. The

equalized data then undergoes a P/S conversion and demodulation, creating estimate of the transmitted binary data. The following equation shows the relationship between transmitted signal S_k and received signal R_k:

$$R_k = S_k . H_k + Z_k \tag{4.4}$$

Z_k is the frequency domain at the k-th sub-carrier frequency, and

H_k is the channel transfer function at the k-th sub-carrier frequency, where

$$\begin{aligned} H_k &= DFT\{h(n)\} \\ &= DFT\{\tfrac{1}{N}\textstyle\sum_{k=0}^{N-1} H_k \; e^{j2\pi kn/N} \} \qquad n = 0,1, \dots ., N-1 \\ &= \textstyle\sum_{n=0}^{N-1} h(n) \; e^{-j2\pi nk/N} \qquad k = 0,1, \dots .., N-1 \end{aligned} \tag{4.5}$$

Following DFT block, the pilot signals are extracted and the estimated channel $\acute{H}_k$ for the data sub-channel is obtained in channel estimation block. Then the transmitted data is estimated by:

$$\acute{S}_k = \frac{R_k}{\acute{H}_k} \tag{4.6}$$

In order to estimate the channel, pilot symbols are needed. We assume that every p-th sub-carrier contains known pilot symbols S_{pk}. By using these known pilot symbols S_{pk} and the received symbols R_{pk} at those pilot sub-carriers, we can calculate the raw channel estimate

$$R_{pk} = S_{pk} . \acute{H}_{pk} + Z_{pk} \tag{4.7}$$

$$\acute{H}_{pk} = \frac{R_{pk}}{S_{pk}} + \frac{Z_{pk}}{S_{pk}}$$

$$R_{pk} = S_{pk} . H_{pk}$$

$$H_{pk} = \frac{R_{pk}}{S_{pk}}$$

$$\acute{H}_{pk} = \frac{R_{pk}}{S_{pk}} + \frac{Z_{pk}}{S_{pk}} = H_{pk} + Z'_{pk} \tag{4.8}$$

where Z_{pk} is the noise contribution at the pk-th subcarrier, Z'_{pk} Is a scaled noise contribution at that subcarrier.

In the next sections, we investigate the impact of pilot allocation on channel estimation performance, and explore the different methods used for channel estimation.

4.3 Pilot Allocation and Time-Frequency Interpretation

The fading channel of the OFDM system in Figure 10 can also be described using a two-dimensional lattice in the time-frequency domain which is sampled at pilot positions and the channel characteristics between pilots are estimated by interpolation [Shen, et al., (2010)].

Figure 11 shows time- frequency domain representation where evolved universal terrestrial radio access network (EUTRAN) symbols are transmitted sequentially. In this figure an OFDM symbol consists of N_c subcarriers, symmetrically arranged around the carrier frequency (or DC). There is no data transmitted on DC and edge sub-carriers in order to avoid interference in adjacent bands.

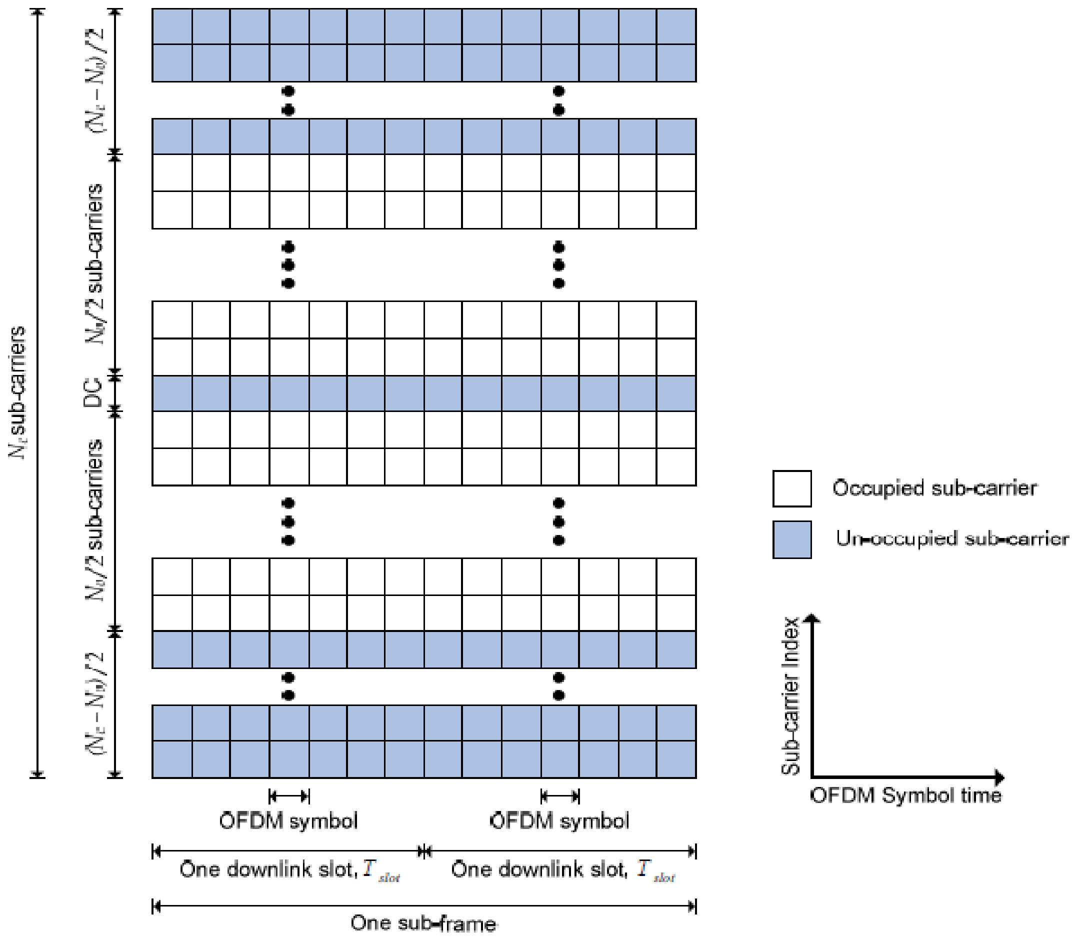

Figure 11 Time-Frequency lattice for OFDM transmission

The subcarriers transmitting pilot information are often called pilot symbols. At the receiver the pilot information is used in order to estimate the wireless channels. By pilot information, we mean the position and the values which modulate those subcarriers. There are different possibilities exists for the allocation of pilots in time-frequency domain of an OFDM system and this is shown in Figure 12 below.

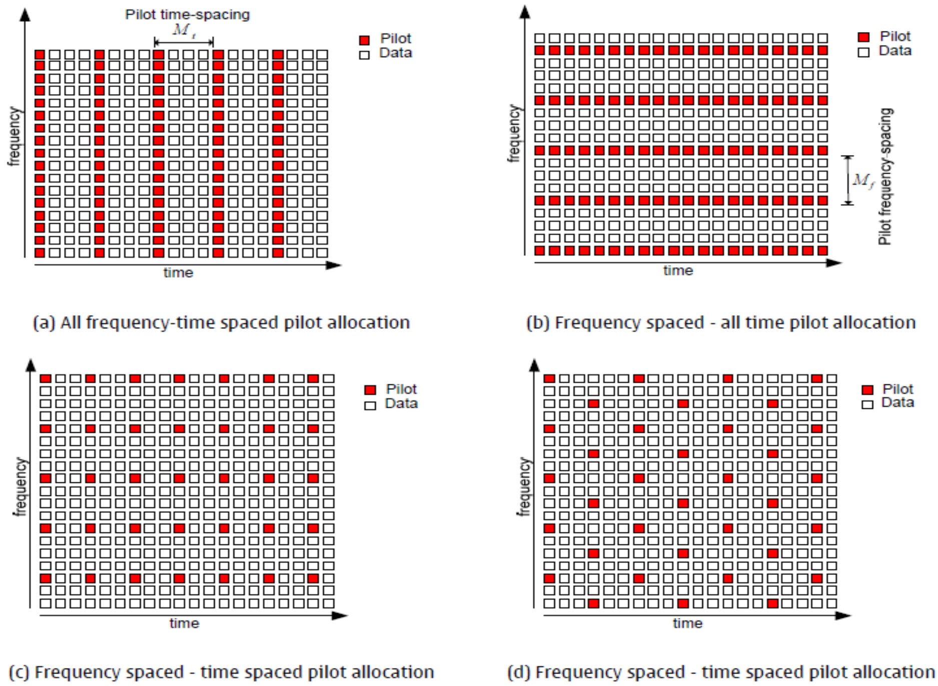

Figure 12 Different possibilities for pilot allocation

The estimation of channel can be achieved by inserting pilot tones into all of the subcarriers of OFDM symbols with a specific period and this arrangement is referred to as *Block-Type* pilot arrangement or inserting pilot tones into some of the subcarriers for each OFDM symbol and it is referred to as *Comb-Type* pilot arrangement [Tufvesson and Maseng (1997)].

4.3.1 **Block-Type Pilot Arrangement**

Figure 12a shows *block-type* pilot arrangement which is developed under the assumption of slow fading channel, in which the channel is assumed to be constant over one or more OFDM symbol periods [Coleri, et al., (2002)]. The task here is to estimate the channel conditions given the received signals and pilot signals, with or without using certain knowledge of the channel statistics. So the receiver uses the estimated channel conditions to decode the received data inside the block until the next pilot symbol arrives [Vidhya and Kumar (2013)]. The estimation of this channel can be based on LS or MMSE.

The time spacing M_t between the pilots should fulfill [Moon and Choi (2000)]

$$M_t \approx \frac{1}{2}\frac{1}{2T_{sub}f_d} \tag{4.9}$$

where

T_{sub} is the symbol time

f_d is the maximum Doppler spread

4.3.2 **Comb-Type Pilot Arrangement**

Figure 12b shows Comb-type pilot arrangement where the pilot tones are multiplexed with the data within the OFDM symbol [Ozdemir and Arslan (2007)]. The main idea behind this type of arrangement is to first estimate the channel conditions at the pilot subcarriers and then estimate the channel at the data subcarriers, given LS estimates at pilot subcarriers, received signals and maybe certain additional knowledge of the channel statistics [Speth (2001)]. The estimation of the channel at the pilot subcarriers can be based on LS, ML and PCMB.

The frequency-spacing M_f between pilots should fulfill the requirements of the 2-D sampling theorem as:

$$M_f \approx \frac{1}{2}\frac{1}{2\Delta f \tau_{max}} \tag{4.10}$$

where τ_{max} is the maximum excess delay of the channel and Δf is the sub carrier bandwidth

4.4 Channel Estimation Methods

Channel estimation in OFDM is a two-dimensional (2-D) problem where it is needed to be estimated in the time - frequency domain.

The two-dimensional (2-D) methods could be applied to estimate the channel from pilots [Beant and Harjinder (2015)]. Due to the computational complexity of 2-D estimators, the scope of channel estimators can be limited to 1-D. The basic idea behind 1-D estimators is to estimate the channel in one dimension (say frequency) and later estimate the channel in the second dimension (say time), therefore obtaining a 2-D channel estimate [Lee (1989)].

There are several methods for the estimation of channel, and these methods can be characterized into three categories:

1- Least-Square (LS) Estimator

2- Minimum Mean Square Error (MMSE) Estimator

3- Linear Minimum Mean Square Error (LMMSE) Estimator

4.4.1 **Least-Squares (LS) Estimator**

Channel estimation is performed by calculating an error using mathematical correlation algorithms. The fundamental algorithm for most of the channel estimation algorithms derived from the theory of the LS channel estimation technique [Lee (1989)]. The impulse response of multipath channel could be written as [Li, (2000)]:

$$h(t,\tau) = \sum_{k=0}^{L-1} \gamma_k(t)\delta(t-\tau_k) \tag{4.11}$$

where τ_k is the delay of k^{th} path, $\gamma_k(t)$ is the amplitude of k^{th} path, and is the L is the number of sub-carriers, respectively.

From equation (4.4)

$$R_k = S_k.H_k + Z_k$$

Then

$$Z_k = R_k - S_k . H_k \tag{4.12}$$

The LS estimate $\acute{H}_{k,LS}$ of H_k is calculated by minimizing the following squared error quantity [Van de Beek, et al., (1995)]:

$$\acute{H}_{k,LS} = arg\min_{H_k} \|Z_k\|^2 \tag{4.13}$$

where $\|Z_k\|^2 = (Z_k)^H . (Z_k)$ and $()^H$ is the conjugate transpose operation. Equation (4.13) becomes:

$$\acute{H}_{k,LS} = arg\min_{H_k} \{(Z_k)^H . (Z_k)\} \tag{4.14}$$

Substituting (4.12) in (4.14), yield

$$\acute{H}_{k,LS} = arg\min_{H_k} \{(R_k - S_k . H_k)^H . (R_k - S_k . H_k)\} \tag{4.15}$$

$$= arg\min_{H_k} \{R_k^H R_k - R_k^H S_k H_k - S_k^H H_k^H R_k + S_k H_k S_k^H H_k^H\} \tag{4.16}$$

Now let

$$R_k^H R_k - R_k^H S_k H_k - S_k^H H_k^H R_k + S_k H_k S_k^H H_k^H = J(H_k) \tag{4.17}$$

By minimizing equation (4.17)

$$\frac{\partial}{\partial H_k^H} J(H_k) = 0$$

$$\frac{\partial}{\partial H_k^H} \{ R_k^H R_k - R_k^H S_k H_k - S_k^H H_k^H R_k + S_k H_k S_k^H H_k^H\} = 0 \tag{4.18}$$

We get

$$\frac{\partial}{\partial H_k^H} J(H_k) = 0 - 0 - S_k^H R_k + S_k^H S_k H_k = 0 \tag{4.19}$$

From the above equation, the least-square estimate $\acute{H}_{k,LS}$

$$\acute{H}_{k,LS} = (S_k^H S_k)^{-1} (S_k^H R_k) \tag{4.20}$$

Without using any knowledge of the statistics of the channels, the LS estimators are calculated with very low complexity, but they suffer from a high mean-square error since it does not take into account of the effect of noise on the signal [Van de Beek, et al., (1995)].

4.4.2 **Minimum Mean Square Error (MMSE) Estimator**

The minimum mean-square error estimator is widely used in the OFDM channel estimation because it is optimal in terms of mean square error (MSE) in the presence of AWGN [Athaudage and Jayalath (2004)]. Many channel estimation techniques are indeed a subset of MMSE channel estimation technique, as observed in [Ozdemir and Arslan (2007)]. The MMSE estimator employs the operating signal-to-noise ratio (SNR), channel correlation function and the second-order statistics to minimize the MSE [Morelli and Mengali (2001)].

From figure 10, we show that the relationship between transmitted signal S_k and received signal R_k is equal to:

$$R_k = DFT_N\{IDFT_N\{S_k\} * h(n) + z(n)\} \tag{4.21}$$

$$= DFT_N\big\{IDFT_N\{S_k\}\big\} * DFT_N\{h(n)\} + DFT_N\{z(n)\}$$

$$= DFT_N\{s(n)\}. DFT_N\{h(n)\} + DFT_N\{z(n)\} \tag{4.22}$$

where

$R_k = [R_0 \quad R_1 \quad \dots\dots \quad R_{N-1}]^T$ is the received vector

$S_k = [S_0 \quad S_1 \quad \dots\dots \quad S_{N-1}]^T$ is the vector of transmitted signal

$H_k = [H_0 \quad H_1 \quad \dots\dots \quad H_{N-1}]^T$ is the sampled frequency response, and

$Z_k = [Z_0 \quad Z_1 \quad \dots\dots \quad Z_{N-1}]^T$ is the vector of complex Gaussian variables

The DFT matrix is [Van de Beek, et al., (1995)]:

$$F = \begin{bmatrix} W_N^{00} & \cdots & W_N^{0(N-1} \\ \vdots & \ddots & \vdots \\ W_N^{(N-1)0} & \cdots & W_N^{(N-1)(N-1)} \end{bmatrix} \tag{4.23}$$

where

$W_N^{nk} = e^{-j2\pi nk/N}$, $DFT_N\{h(n)\} = H_k = Fh$ and $DFT_N\{z(n)\} = Z_k = Fz$

Equation (4.22) becomes

$$R_k = S_k.Fh + Fz \tag{4.24}$$

Now, let us denote R_{hh}, $R_{H_kH_k}$ and $R_{R_kR_k}$ as the auto-covariance matrix of h, H_k and R_k, respectively. And we also define R_{hR_k}as the cross-covariance matrix between h and R_k [Vidhya and Kumar (2013)].

If the time domain channel vector h is a Gaussian and uncorrelated with the channel noise $z\,(n)$, the frequency domain MMSE estimate of h is given by [Coleri,et l.,(2002)].

$$\acute{H}_{MMSE,k} = F\acute{h}_{MMSE} \tag{4.25}$$

where

$$\acute{h}_{MMSE} = R_{hR_k}R_{R_kR_k}^{-1}.R_k \tag{4.26}$$

$$R_{H_kH_k} = E\{H_kH_k^H\} \tag{4.27}$$

$$= E\{(Fh)(Fh)^H\}$$

$$= E\{FF^Hhh^H\}$$

$$= FF^HR_{hh} \tag{4.28}$$

$$R_{hR_k} = E\{hR_k^H\} \tag{4.29}$$

$$= E\{h\{S_kFh + Z_k\}^H\}$$

$$= E\{hS_k^HF^Hh^H + h^HZ_k^H\}$$

$$= E\{hS_k^HF^Hh^H\} + E\{h^HZ_k^H\}$$

$$= S_k^HF^HE\{hh^H\} + 0$$

$$= F^HS_k^HR_{hh} \tag{4.30}$$

and

$$R_{R_kR_k} = E\{R_kR_k^H\} \tag{4.31}$$

$$= E\{(S_kFh + Z_k).(S_kFh + Z_k)^H\}$$

$$= E\{S_k\,S_k^HFhF^Hh^H + S_kFhZ_k^H + Z_kS_k^HF^Hh^H + Z_kZ_k^H\}$$

Since the time domain channel vector h is uncorrelated with the channel noise $z(n)$ [Coleri, et al., (2002)], then:

$$R_{R_kR_k} = E\{S_k\,S_k^HFhF^Hh^H + Z_kZ_k^H\}$$

$$= S_k\, S_k^H F F^H R_{hh} + \sigma_z^2 . I_N \tag{4.32}$$

where σ_z^2 is the noise variance, $E\{|Z_k|^2\}$, and I_N is the $N \times N$ Identity matrix.

Substituting equation (4.30) and equation (4.32) in equation (4.26), yields

$$\acute{h}_{MMSE} = R_{hR_k} R_{R_k R_k}^{-1} . R_k$$
$$= F^H S_k^H R_{hh} (S_k\, S_k^H F F^H R_{hh} + \sigma_z^2 . I_N)^{-1} . R_k \tag{4.33}$$

Finally, from the above equation, the frequency domain MMSE estimator can be calculated by [Van de Beek, et al., (1995)]:

$$\acute{H}_{MMSE,k} = F \acute{h}_{MMSE}$$
$$= F F^H S_k^H R_{hh} (S_k\, S_k^H F F^H R_{hh} + \sigma_z^2 . I_N)^{-1} . R_k \tag{4.34}$$

From equation (4.20)

$$R_k = S_k . \acute{H}_{k,LS} \tag{4.35}$$

Then equation (4.34) becomes

$$\acute{H}_{MMSE,k} = F F^H S_k^H R_{hh} (S_k\, S_k^H F F^H R_{hh} + \sigma_z^2 . I_N)^{-1} . S_k \acute{H}_{k,LS} \tag{4.36}$$

Since $F F^H R_{hh} = R_{H_k H_k}$, equation (4.36) becomes

$$\acute{H}_{MMSE,k} = R_{H_k H_k} S_k^H S_k \left(S_k\, S_k^H R_{H_k H_k} + \sigma_z^2 . I_N\right)^{-1} . \acute{H}_{k,LS}$$
$$= R_{H_k H_k} S_k^H S_k (S_k\, S_k^H)^{-1} \left(R_{H_k H_k} + \sigma_z^2 . (S_k\, S_k^H)^{-1}\right)^{-1} . \acute{H}_{k,LS}$$
$$= R_{H_k H_k} \left(R_{H_k H_k} + \sigma_z^2 . (S_k\, S_k^H)^{-1}\right)^{-1} . \acute{H}_{k,LS} \tag{4.37}$$

MMSE estimator yields much better performance than the LS estimator, especially under the low SNR scenarios [Mnwinder,et al., (2011)]. But there are two major drawbacks in this estimator, firstly its High computational complexity, since the matrix inversion of size $N \times N$ is needed each time data in S_k Changes and secondly it requires one to know the correlation of the channel and the operating SNR in order to minimize the MSE between the transmitted and received signals [Coleri, et al., (2002)].

4.4.3 **Linear Minimum Mean Square Error (MMSE) Estimator**

The LMMSE channel estimator provides much accurate channel estimation approximation when compared to the LS channel estimation technique. This technique employs calculation of channel effect along with an LS channel estimation. This technique shows very good performance, but at the cost of too high complexity as it requires $N \times N$ number of complex multiplications for an N-subcarrier OFDM system [Van de Beek, et al., (1995)].

From $\acute{H}_{MMSE,k}$ in equation (4.37) we could find that the channel estimator needs to get the inverse matrix of $R_{H_k H_k} + \sigma_z^2 . (S_k\, S_k^H)^{-1}$. Because $(S_k\, S_k^H)^{-1}$ are not the same in different OFDM symbol, its inverse matrix should be updated every time for the different OFDM symbol,

which needs much computation. A simplification of MMSE estimator is to replace the $(S_k\, S_k^H)^{-1}$ by its expectation $E\{(S_k\, S_k^H)^{-1}\}$, which means the average power of all subcarriers replace the instantaneous power of each subcarrier in order to reduce the computation, since matrix inversion of $R_{H_kH_k} + \sigma_z^2.(S_k\, S_k^H)^{-1}$ is no longer needed [Ozdemir and Arslan (2007)].

Assuming the same signal constellation on all tones and equal probability on all constellation points, we get

$$E\{(S_k\, S_k^H)^{-1}\} = E\left\{\frac{1}{|S_k|^2}\right\} I \tag{4.38}$$

where I is the identity matrix

Let the average of SNR is

$$\overline{SNR} = \frac{E\{|S_k|^2\}}{\sigma_z^2} \tag{4.39}$$

Since

$$\sigma_z^2 = \frac{E\{|S_k|^2\}}{\overline{SNR}} \tag{4.40}$$

The term $\sigma_z^2.(S_k\, S_k^H)^{-1}$ is approximated by

$$\begin{aligned} \sigma_z^2.(S_k\, S_k^H)^{-1} &= \sigma_z^2 E\{(S_k\, S_k^H)^{-1}\} \\ &= \sigma_z^2 E\left\{\frac{1}{|S_k|^2}\right\} I \\ &= \frac{E\{|S_k|^2\}}{\overline{SNR}}.E\left\{\frac{1}{|S_k|^2}\right\} I \\ &\approx \frac{\beta}{\overline{SNR}}\, I \end{aligned} \tag{4.41}$$

where β is a constant depending only on the signal constellation and it's defined as

$$\beta = E\{|S_k|^2\}.E\left\{\frac{1}{|S_k|^2}\right\} \tag{4.42}$$

From equation (4.42), the LMMSE can be written as

$$\acute{H}_{LMMSE,k} = R_{H_kH_k}\left(R_{H_kH_k} + \frac{\beta}{\overline{SNR}}\, I\right)^{-1}.\acute{H}_{k,LS} \tag{4.43}$$

This technique provides much better results, but generate a huge computational complexity as it includes many inverse operations and multiplication operations [Speth (2001)].

4.5 Summary for Pilot-Symbol-Aided Channel Estimator

It is necessary to estimate the channel for coherent systems and using this information to correct the received data. In differential modulation schemes the channel state information is not necessary, but it can help improving the performance of the system. Considering that the wireless channels are very time variant especially mobile radio channels, the task of maintaining and estimating of the channel is not a simple task. And because of that several different techniques have been proposed.

Channel estimation in a wireless communication system is a process in which the characteristic of fading channel is measured in order to modify

the received signal based on that information to correct the received data and to achieve a good use of the channel.

There are many techniques to get an estimation of the channel, most importantly is to insert known symbols also called pilots on the input and then get the response of such symbols to estimate the channel. The channel estimation can be performed by either inserting pilot tones into all of the subcarriers of OFDM symbols with a specific period and this type is called *Block-Type* pilot channel estimation or inserting pilot tones into each OFDM symbol and this type is called *Comb-Type* pilot channel estimation.

In this chapter, the LS estimation technique is presented as it is needed by many estimation techniques as an initial estimation, followed by the MMSE estimator and LMMSE estimator. The MMSE estimator has a good performance, but high complexity. The LS estimator has low complexity, but its performance is not as good as that of MMSE estimator. The LMMSE provide much better performance, but generate a huge computational complexity

4.6 Introduction to Simulation Results

Channel estimation plays an important part in an ODFM system, where it's used to increase the capacity of orthogonal frequency division multiple access (OFDMA) system by improving the performance of the system in terms of bit error rate.

Channel estimation is defined as the process of characterizing the effect of the physical channel on the input data sequence [Paul, et al., (2011)]. If the channel is assumed to be linear, the channel estimate is simply the estimate of the impulse response of the system. A "good" channel estimate is one where some sort of error minimization criteria is satisfied [Lekshmi, et al., (2013)].

To facilitate the channel characteristics estimation, pilot symbols inserted in both time and frequency domains. These pilot symbols provide an estimate of the channel at given locations within a sub-frame. Through interpolation, it is possible to estimate the channel across an arbitrary number of sub-frames.

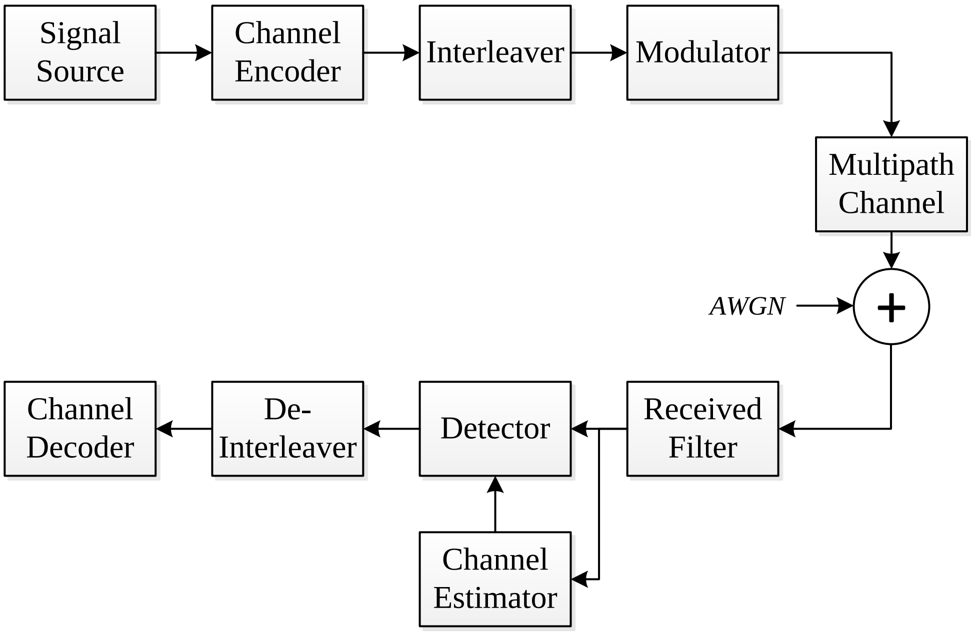

Figure 13 Generic simulation layout for communications systems

Figure 13 shows a generic simulation layout for communications systems, which exploits channel estimation and signal detection operations in equalization. In this figure, the digital source is protected by channel coding and interleaved against fading phenomenon, after which binary signal is modulated and transmitted over multipath fading channel. AWGN is added, and the combined signal is received. Due to multipath channel, there is some ISI in the received signal. According to this, a signal detector needs to know the channel impulse response (CIR) characteristics in order to ensure successful equalization (i.e. Removal of ISI). Finally, after the detection process the signal is de-interleaved and channel decoded to extract the original data message [Batav and Chourasiya (2013)].

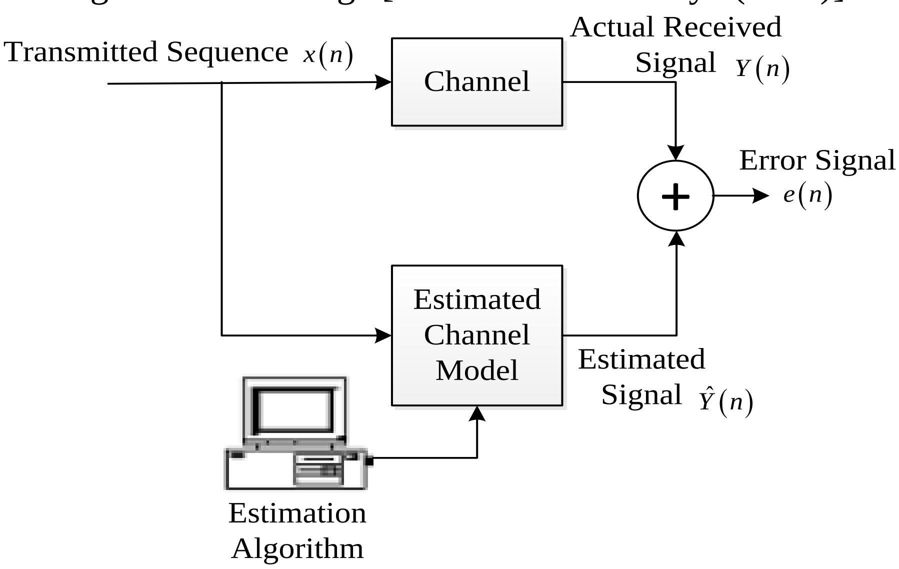

Figure 14 General digital Channel Estimation Procedure

Figure 14 represents a digital channel estimation procedure. In this figure $e(n)$ is the estimation error. The main objective of most channel estimation algorithms is to minimize MSE, $E[e^2(n)]$, while utilizing as little computational resources as possible in the estimation process.

This chapter starts with the comparisons of OFDM using Binary Phase Shift Keying (BPSK) in AWGN and Rayleigh multipath channel. The simulation setups and the results of pilot-based channel estimation in OFDM system will be also discussed. We present the simulation results for channel estimation of the MMSE estimator in 1-D pilot symbol aided where the estimation and as well as the signal are made from one dimensional (1-D) frame, and in 2-D pilot symbol aided which is made to estimate two dimensional signal having a multi - frame.

4.7 Performance Comparison of Digital Modulation Techniques over AWGN

The performance of various modulation techniques in AWGN channel investigated. One of the most important parameters in digital communications is the energy per bit to the noise power spectral density ratio (E_b/N_0). It is a normalized signal-to-noise ratio (SNR) measure. It is especially useful when comparing the bit error rate (BER) performance of different digital modulation schemes without considering bandwidth into account. Figure 15 compares the bit-error rates of M-PSK and M-QAM. It can be noted that BER for all systems decrease monotonically as E_b/N_0 increases. As the value of M (i.e. the number of bits in a symbol) increase, the error rate also increases. Further, it is observed from the simulation results that as the signal power increases, the error rate decreases sharply.

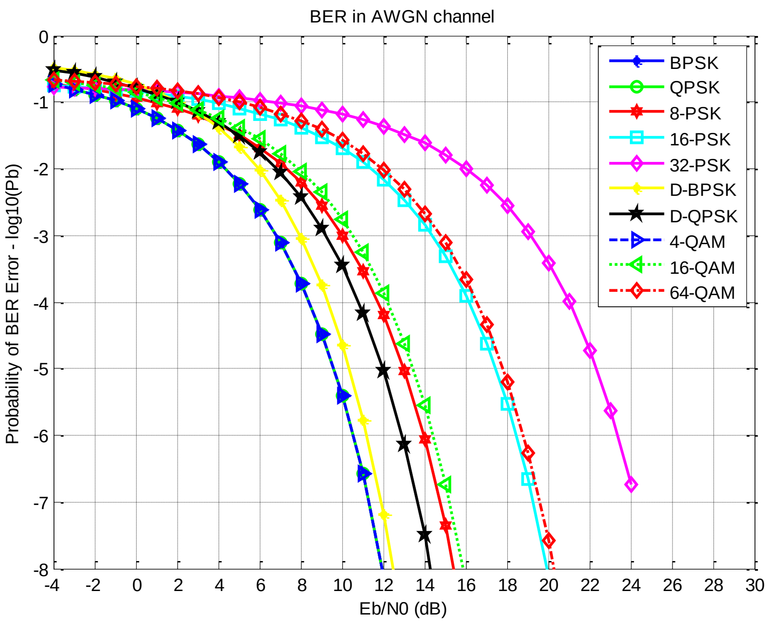

Figure 15 E_b/N_0 vs. BER in AWGN channel

4.8 Comparison between AWGN and Rayleigh Channel for BPSK Modulation

The simulated and theoretical performance curves (E_b/N_0 vs. BER) for BPSK modulation over AWGN and Rayleigh fading channel are given in Figure 16.

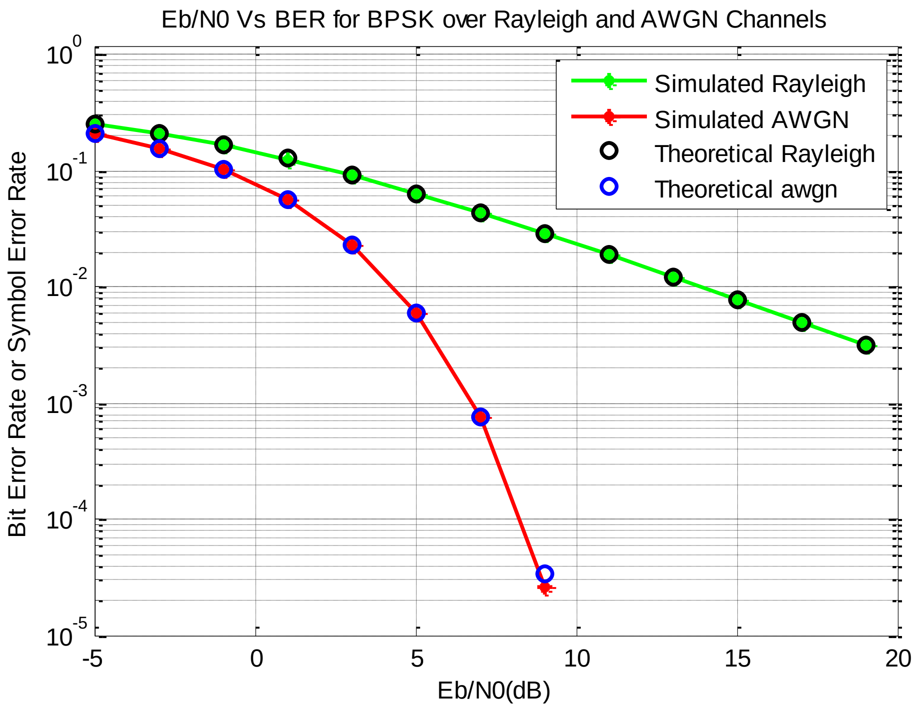

Figure 16 E_b/N_0 vs. BER for BPSK over AWGN and Rayleigh Channels

From the figure we conclude that, AWGN channel works only for small values of E_b/N_o (without fading). At large values of E_b/N_0 (with fading) AWGN diminishes.

The performance of AWGN channel is the best as it has the lowest BER under the BPSK modulation scheme. However, the performance of Rayleigh fading channel is the worst as BER of this channel has been much affected by noise under the BPSK modulation scheme.

4.9 Bit Error Rate Performance of OFDM-BPSK with AWGN and Rayleigh Multipath Channel

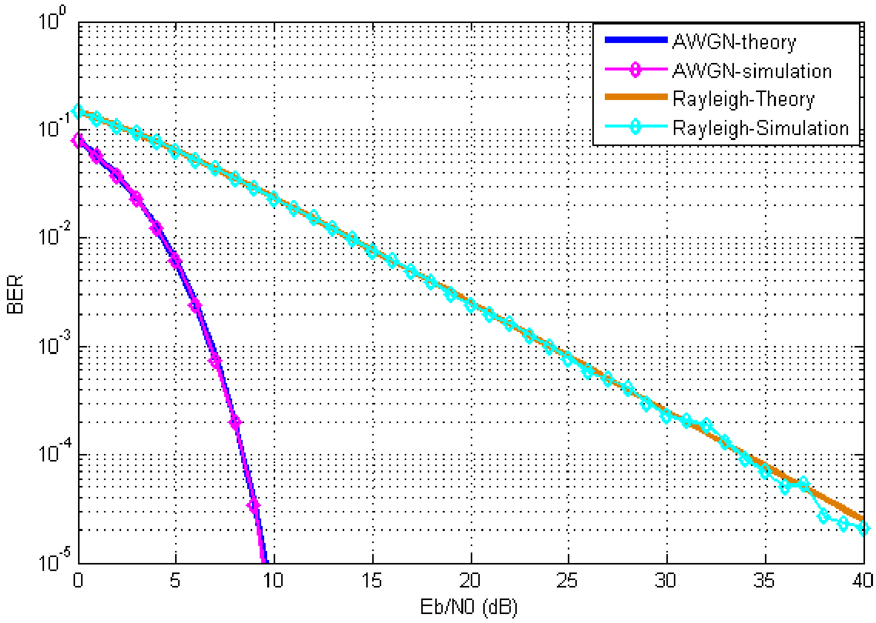

Figure 17 E_b/N_0 vs. BER performance for OFDM-BPSK over AWGN and Rayleigh Channels

Figure 17 shows that the OFDM-BPSK modulation has no advantages over a normal BPSK system in AWGN. However, OFDM proves to be effective in multipath environment due to the orthogonality criteria of the OFDM sub-carriers that avoid the effect of ICI and adding the cyclic prefix that prevent the system from having ISI. The simulated results prove that simulated BER of BPSK is the same as that of theoretical BER of BPSK. Furthermore, the reported BER can be further reduced by using channel estimation or suitable diversity scheme.

4.10 Comparison of Pilot-based Channel Estimation

Figure 18 shows the comparison of pilot-based estimation with and without comb pilot-based channel estimation. In the simulation, comb-type and the LS estimator are used. Pilot-based estimation shows better performance compared with no channel estimation. As analyzed in chapter 4, channel impulse response is estimated by the algorithm of pilot-based channel estimation, in order for the receiver to get accurate received signal.

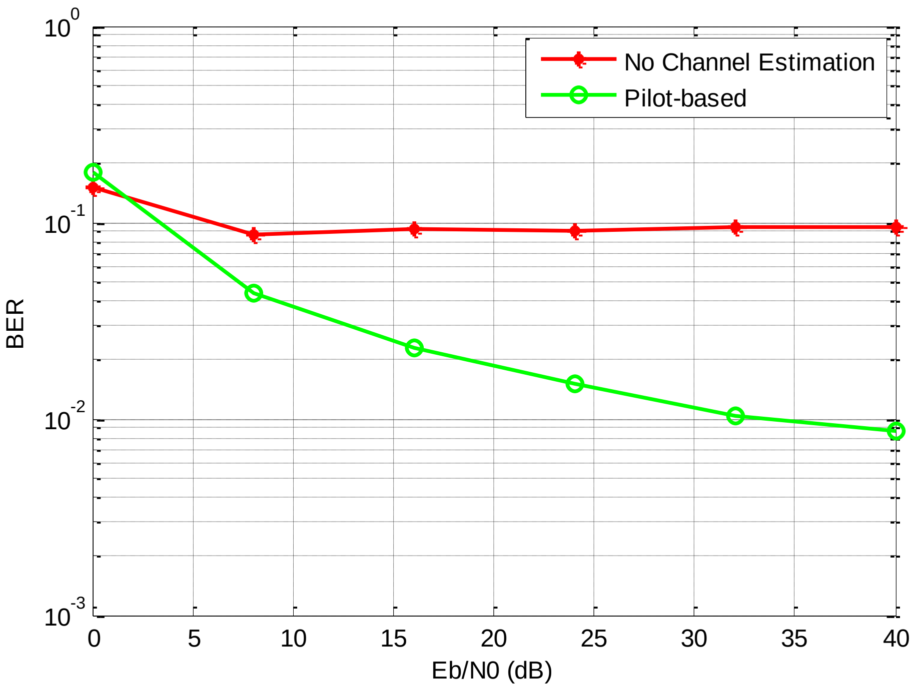

Figure 18 Comparison of OFDM system with and without comb pilot-based channel estimation (LS)

4.11 Comparison between MMSE and LS Estimators

This section discusses the results of the simulation that were performed based on the mathematical modeling discussed in sections 4.4.1and 4.4.2.

The simulation results in Figure 19 below show the mean square error (MSE) of channel estimation at different SNRs in dB for LS and MMSE Estimators. It is clear that as SNR increases mean square error decreases for both LSE and MMSE.

From table 1, it is clear that at lower SNR values, for example 5 dB, the MSE due to LS is 0.07878 and MMSE is 0.02167 respectively. At higher values of SNR, for example 25 dB, the MSE due to LS is 0.0007763 and MMSE is 0.0003792 respectively. As can be observed from the table, the MMSE performs better than LS estimation in general.

The MMSE estimator assumes a priori knowledge of noise variance and channel covariance. Therefore, the performance of MMSE estimator is better than that of the LS estimator. Moreover, its complexity is large compared to the LS estimator.

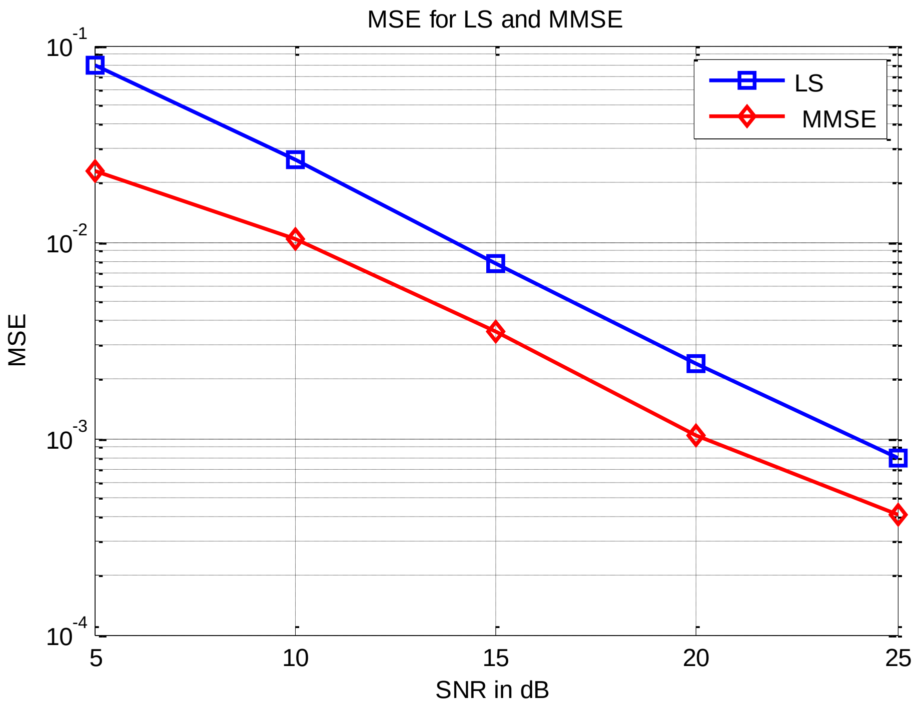

Figure 19 Mean Square Error for LSE and MMSE estimators at different SNRs

Table 1 MSE for LS and MMSE at different SNRs

SNR	MES for LS	MES for MMSE
5	0.07878	0.02167
10	0.02546	0.00966
15	0.008301	0.003848
20	0.002319	0.001112
25	0.0007763	0.0003792

4.12 Comparison between LMMSE and LS Estimators

Figure 20 compares between MSE performance of LS and LMMSE Estimation algorithms. Obviously, The performance of LMMSE is better than LS, as it has the accurate channel statistical parameters and the influence of noise is considered. However, LMMSE algorithm needs much more complex computation due to the channel correlation [Yang, et al., (1977-1987)].

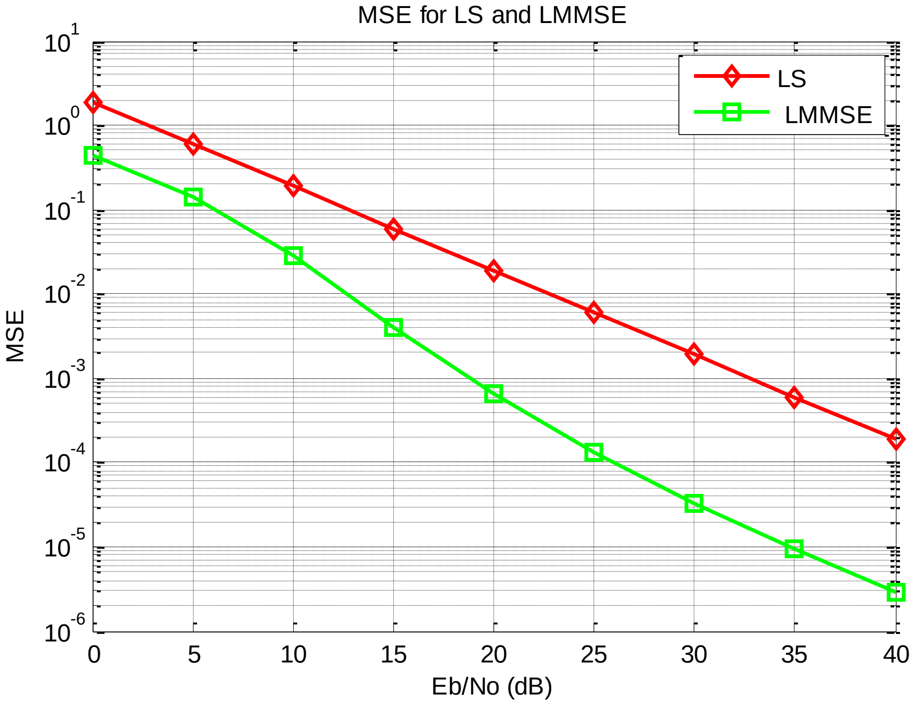

Figure 20 Mean Square Error for LS and LMMSE estimators at different E_b/N_os

4.13 One-Dimensional (1-D) Pilot-Symbol-Aided

One Dimensional (1-D) Pilot-Symbol-Aided for OFDM communication system simply, is a method used to estimate the channel using known symbols added to the information symbols by arithmetic technique to make it possible to recognize any change or even error happen to these symbols, hence we have some knowledge to the channel at the time of sending data. This can save time and/or frequency slots and the bandwidth of the information to be sent.

Figure 21 shows the block diagram for channel estimation in one-dimensional pilot-symbol-aided and Figure 22 demonstrates how we select the pilot symbols.

The procedure used in (1-D) pilot-symbol-aided to estimate the channel is as follows:

1. Few bits are selected from the transmitted frame where the locations of these bits in the frame are known.
2. In the receiver, the received bits are divided by the selected pilot bits.
3. Interpolation in these bits to estimate the CIR is applied.
4. Low Pass Filter is used.
5. The MMSE is calculated

Regarding one dimensional channel estimator, the wireless channel is assumed to be a frequency selective fading channel. For this channel, one dimensional channel estimator is applied for three cases namely;

1. A frame with 64 bits is taken and one pilot symbol per 16 bits is used.
2. A frame with 64 bits is taken and one pilot symbol per 8 bits is used.
3. A frame with 64 bits is taken and one pilot symbol per 4 bits is used.

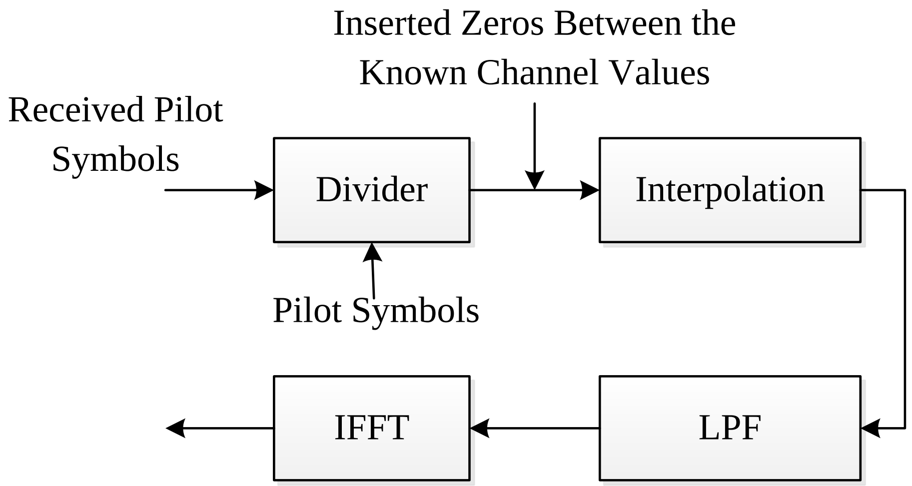

Figure 21 Block diagram for channel estimation in one dimensional pilot-symbol-aided

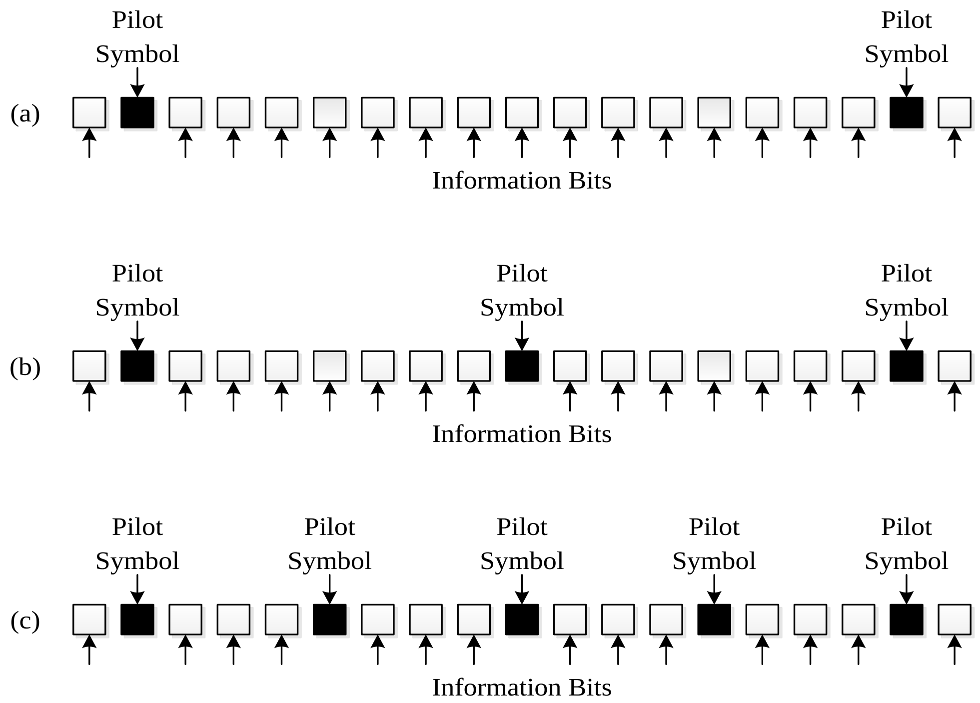

Figure 22 Distribution of Pilot Symbols (a) One Pilot Symbol every 16 bits (6.25%), (b) One Pilot Symbol every 8 bits (12.5%), (c) One Pilot Symbol every 4 bits (25%)

Figure 23 illustrates the Mean Square Error (MSE) versus Signal-to-Noise Ratio SNR, using 64 bits frame with 6.25%, 12.5%, 25% number of pilot symbols per number of information bits (one pilot symbol every

sixteen, eight or four bits of information “1/16, 1/8, 1/4”) as shown in Figure 22 above.

It can be seen that MSE is inversely proportional to the number of available pilot symbols, as the number of pilot symbols increase, the MSE decrease and therefore, the performance of the system will be increased.

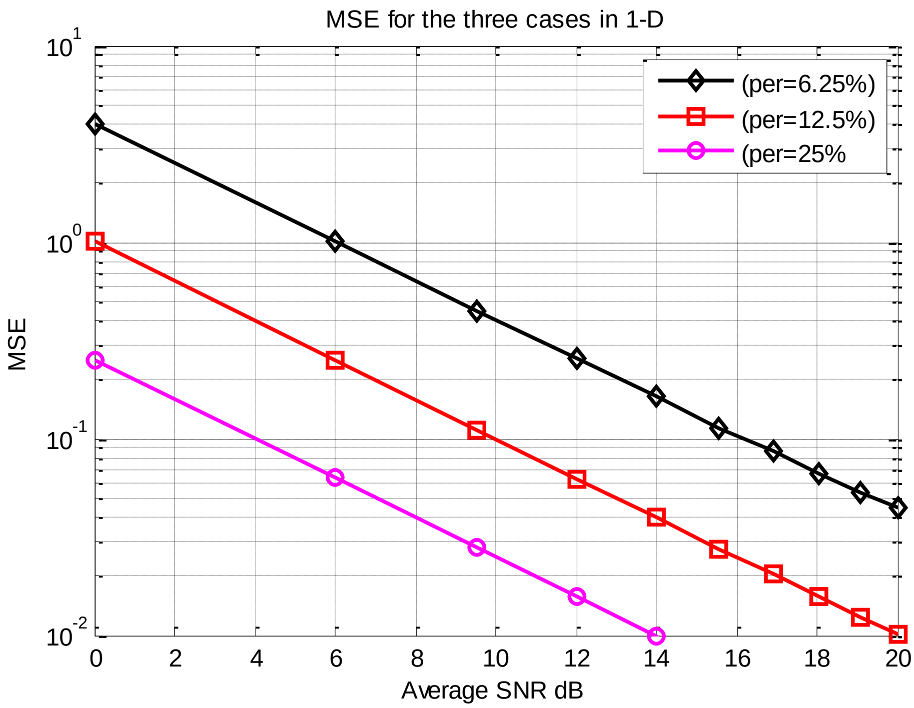

Figure 23 MSE for the three cases in 1-D (6.25% above, 12.5% middle and 25% below)

4.14 Two-Dimensional (2-D) Pilot-Symbol-Aided

Two dimensional Pilot-Symbol-Aided deals with multi-frames simultaneously where every frame depends on the other. In 2-D the estimation does not depend only in the little bits from one frame, but also on all the frames that are used, as shown in Figure 24. This method is more effective and gives more perspective, since it gets information about the channel from multiple frames rather than 1-D, which get the information only from one frame. Figure 25 demonstrates how pilot symbols are selected.

The procedure used in (2-D) pilot-symbol-aided to estimate the channel is as follows;

1. Few bits are selected in each frame in some arithmetic way by knowing their exact locations.
2. At the receiver, the received bits are divided by the selected pilot bit
3. Interpolation in these bits to estimate the CIR is applied.
4. Low Pass Filter is used.
5. The MMSE is calculated.

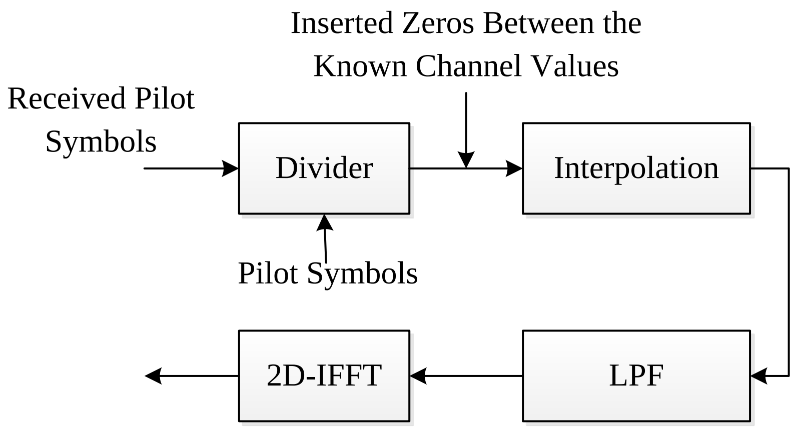

Figure 24 Block diagram for channel estimation in two dimensional pilot-symbol-aided

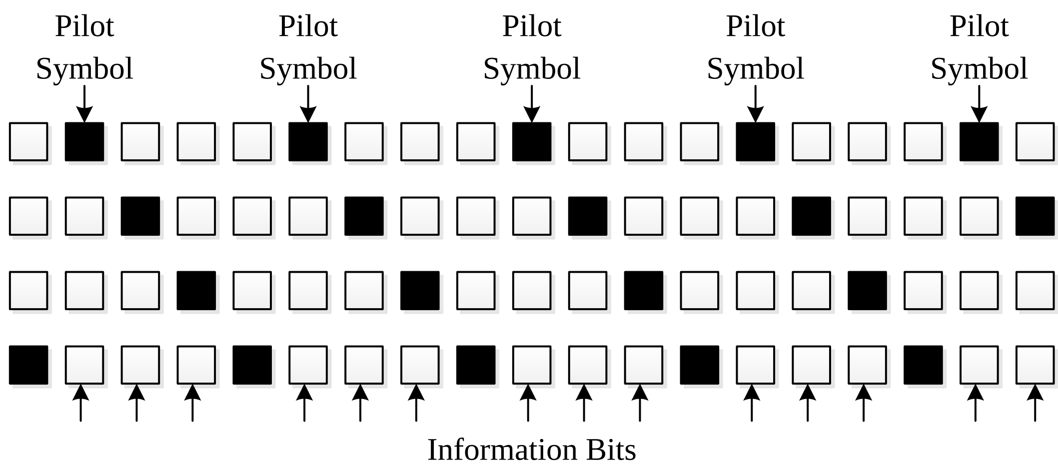

Figure 25 Distribution of Pilot Symbols (One Pilot Symbol every 4 bits (25%))

In two dimensional (2-D) channel estimator, the wireless channel is assumed to be a frequency selective fading channel. For this channel, two dimensional channel estimators are applied for three cases namely;

1. An OFDM, multi-frame with 64 bits for each frame is taken and one pilot symbol per 16 bits is used
2. A multi-frame with 64 bits each is taken and one pilot symbol per 8 bits is used
3. A multi-frame with 64 bits each is taken and one pilot symbol per 4 bits is used

Figure 26 illustrates the Mean Square Error (MSE) vs Signal-to-Noise Ratio SNR, using 64 bits frame with 6.25%, 12.5%, 25% number of pilot symbols per number of information bits (one pilot symbol every sixteen, eight or four bits of information “1/16, 1/8, 1/4”) as shown in Figure 25 above.

It can be noted from the above graph that as the number of pilot symbols increases, the MSE decreases, which means that the performance of the system will be increased.

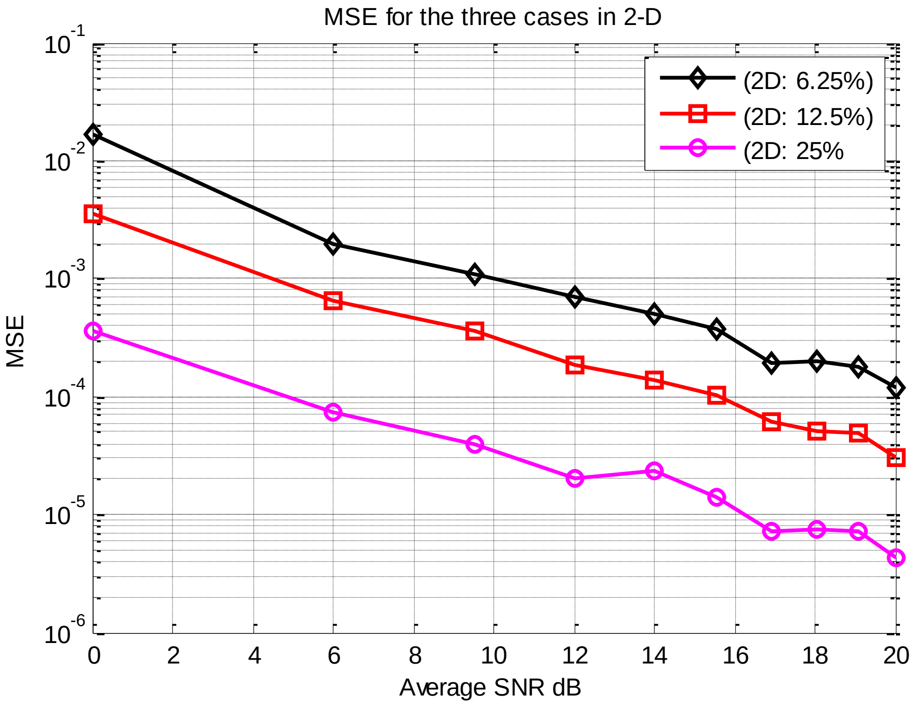

Figure 26 The MSE versus SNR for (6.25%, 12.5% and 25%) 2-D pilot symbols

4.15 Comparison between One-Dimensional (1-D) and Two-Dimensional Pilot-Symbol-Aided

Figure 27 shows the MSE for the six cases that we studied brought together. From Table 2 and Table 3 it can be seen that the performance of the two-dimensional channel estimator outperforms significantly the performance of one-dimensional channel estimator. This is because the interpolation between estimated values of the channel in two-dimensional filtering is evaluated in two dimensions; where it is evaluated in one dimension in one-dimensional estimator.

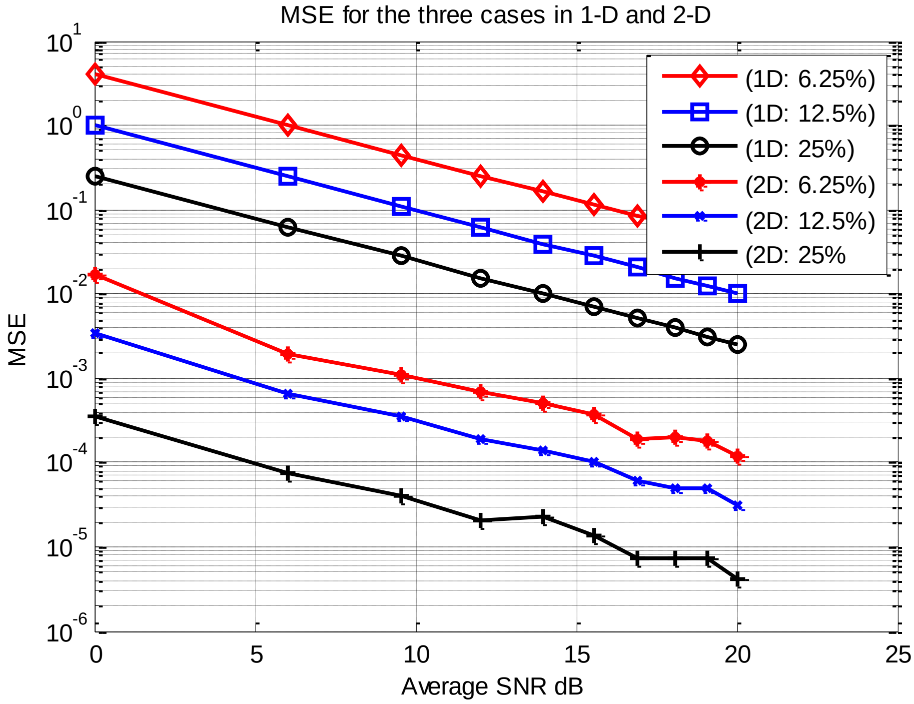

Figure 27 The MSE versus SNR for 6 cases (6.25%, 12.5% and 25%) 1-D pilot symbols and (6.25%, 12.5% and 25%) 2-D pilot symbols

Table 2 MSE for 3 cases (6.25%, 12.5% and 25%) 1-D pilot symbols at different SNRs

	SNR	0 dB	6 dB	12 dB	18 dB
Number of Pilot Symbols per Number of Information Bits	6.25%	4.001	1.005	0.2522	0.06684
	12.5%	0.9958	0.2511	0.06237	0.01563
	25%	0.2506	0.06248	0.01557	0.003901

Table 3 MSE for 3 cases (6.25%, 12.5% and 25%) 2-D pilot symbols at different SNRs

	SNR	0 dB	6 dB	12 dB	18 dB
Number of Pilot Symbols per Number of Information Bits	6.25%	0.01193	0.004666	0.001103	0.0002275
	12.5%	345.2e-5	90.21e-5	27.28e-5	5.778e-5
	25%	48.75e-5	8.462e-5	3.751e-5	0.7088e-5

4.16 Conclusions

In this thesis, pilot-based channel estimation of OFDM system is discussed in details. The focus has been placed on two types of pilot arrangement, namely; block type and comb type. In comparison between block and comb type pilot arrangement, block type of pilot arrangement is suitable to use for slow fading radio channels, where channel impulse response is not changing very fast.

The comb type pilot arrangement is suitable to use for fast fading channel where the channel impulse response is changing very fast, even if one OFDM block is present. SO, comb type of pilot arrangement is not suitable in this case. Both data and pilot carriers in one block of OFDM symbols are used. Pilot carriers are used to estimate the channel impulse response. The estimated channel can be used to get back the data sent by transmitter certainly with some error.

In OFDM system, some core techniques, such as FFT, CP, and equalizer are used. FFT plays an important role in reducing the complexity of OFDM as a multi-carrier communication system. CP eliminate using an equalizer in time domain while in frequency domain, the equalizer is necessary for channel estimation to reduce the ICI and ISI.

The performance of various modulation techniques in AWGN channel was investigated. The simulated results of BER agree with the theoretical values obtained for the modulation schemes. It was observed from the simulation results that the BER performance of AWGN channel improves rapidly and offers a better performance than a Rayleigh fading channel. This is because Rayleigh fading channel is characterized by multipath signal

The performance of three types estimators particularly (LSE, MMSE and LMMSE) has been theoretically and experimentally evaluated for both block type and comb type pilot arrangement. The MMSE estimators assume a priori knowledge of noise variance and channel covariance. Moreover, its complexity is high compared to the LSE estimator. The MMSE estimator has good performance but high complexity. The LSE estimator has low complexity, but its performance is not as good as that MMSE estimator basically at low SNRs. The performance of LMMSE algorithm is better than LS, since the influence of noise is considered in LMMSE. However, LMMSE algorithm needs much more complex computation, which reflects statistical properties of OFDM channel.

In this thesis, we have studied pilot-symbol-aided channel estimation for OFDM system. We investigated this channel estimator based on 1-D and 2-D interpolating filtering. From the simulation results it is noted that as the number of pilot symbols increases the MSE decreases which leads improve the system performance.

At lower SNR values, for example 6 dB, the MSE due to (12.5%) 1-D pilot symbol is 0.2511 and (12.5) 2-D pilot symbols is 0.0009021 respectively. At higher values of SNR, for example 18 dB, the MSE due to (12.5%) 1-D pilot symbol is 0.01563and (12.5) 2-D pilot symbols is 5.778e-005 respectively. Therefore, the performance of the 2-D channel estimator outperforms significantly the performance of the 1-D channel estimator. This is because the interpolation between estimated values of the channel in

2-D filtering is evaluated in two dimensions, where it is evaluated in one dimension in 1-D estimator.

4.17 Future work

Based on this thesis, some of the area having scope for further research as follows:

1. Another type of pilot. Block type and comb type are two extreme types of different fading environment, slow and fast. In practice, a compromised method is needed.
2. For improving accuracy of channel estimation, the Least Mean Square (LMS) iterative algorithm will be added to the receiver which includes a feedback of output and improves the BER performance of system, closed to the ideal channel performance and also the method to determine the pilots location, to improve efficiency of the system may be considered.
3. OFDM system has a bottleneck of performance improvement. And other new techniques are needed to combine with OFDM. Multiple Inputs and Multiple Output (MIMO) system is a popular alternative used in recent wireless communication. And MIMO-OFDM has become a research hotpot in the world.

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